Robustly coordinated operational scheduling of a grid-connected seaport microgrid under uncertainties

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Abstract

The modern seaport system is becoming more electrified by integrating energy storage system, offshore renewable energy sources (RESs), and shore-to-ship power supply system. The energy management and operational scheduling aim to maximise the profit gain by transacting energy with the main grid, reduce the operation cost while minimising the emission at seaport territory. This work proposes a robustly coordinated operational scheduling method of a seaport microgrid as a grid-integrated energy hub under uncertain renewable energy sources power output and load demand. In the day-ahead operation planning, generators, unit commitment and shore-to-ship load schedules are optimised. To address the uncertainty in the renewable energy sources, the day-ahead operation planning is modelled as a two-stage robust optimisation model with conflicting objectives and solved with the column and constraints generation algorithm. These results are used as input parameters for the hour-ahead generation scheduling in the following day. With uncertainty realisation, a shorter time horizon with higher time resolution deterministic optimisation is carried out for the generation dispatch. The proposed method is verified with the IEEE-33 bus distribution network with different uncertainties sets. The simulation results have verified the robustness and effectiveness of the method in dealing with uncertainties. Coordination between day-ahead and hour-ahead not only improves the accuracy and performance of the final dispatch result but also meets the distribution network constraints at generation and load buses.

1 | INTRODUCTION

Currently, more than 90% of the global trade is the result of the marine transportation network, and international maritime organization (IMO) has estimated in its annual report that the reliance on it is expected to be tripled by 2050. Without any corrective actions to improve energy efficiency, the greenhouse gas emission from the marine transportation network is expected to increase by 250% of what was emitted in 2012 [1]. To address these concerns, the concepts of more-electrification of marine transportation are proposed in [2–4]. From these literatures, it is identified that more-electrification of seaport operation is carried out in the following manners: (1) reducing the environmental impact by electrification of port-side equipment and the use of energy-efficient generation resources; and (2) providing cold-ironing power to the berthed-in ships to eliminate the emission from the ships at the port area. Extended electrification of the future seaport is a promising solution that not only offers greenhouse gas emission reduction but also lowers the operational cost and improves operational efficiency. However, with more integrated and interdependent electrical networks, one main research problem is to design an operation framework that addresses the various aspects of the seaport operation. To the best of authors’ knowledge, such research works are yet to be fully established.

Seaport microgrid comprises a variety of essential and flexible electrical loads such as winch, crane, reefer system, electric vehicles, and shore power supply to the berthed-in ships while having great potential to integrate local renewable energy sources (RESs). Currently, many literatures [5–9] suggest that...
more-electrification with the integration of RESs and energy storage system (ESS) is the driving factor for environmental sustainability in the future seaport. In [3], a case study on the impacts of the deliverable renewable energy, ESS capacity, CO2 emission, and cost savings are demonstrated. Optimal sizing and performance evaluation of RESs in future seaport microgrid is illustrated in [6]. However, due to the intermittency and volatility of the non-dispatchable RESs as well as the integration of new types of electrical loads, operation planning of the seaport area has become significantly difficult [7, 8]. Furthermore, seaport microgrid operators are different entities from the main grid. With higher penetration of the offshore RESs owned by the seaport operators, they will want to operate their distributed generation and ESS units to achieve economic gain by selling energy back to the main grid. In this sense, the operation of the seaport is different from the conventional grid-supported or isolated microgrid whose main objective is to address the load demand of the system [9] by relying on the power supply from the main grid. Various aforementioned operational features of seaports encourage adoption of the smart energy management techniques. Given that the electrical loads in seaport areas are located in close proximity, energy management techniques that provide flexibility and controllability in operation planning can be efficiently employed to coordinate the generation and load demand, while mitigating the volatility or uncertainty present in the RESs. To do so, flexible loads in the seaport should be properly scheduled to ensure the economic viability and environmental friendliness that eventually transform it into a prosumer microgrid with a higher level of RESs penetration.

Traditional seaport provides logistic support to the berth-in-ship such as berth allocation, loading, and unloading of cargo. During which the onboard generators (DGs) on the ships are kept on to meet the electrical load demands onboard ship. Such operation results in the excessive emission of greenhouse gas and pollutant in the seaport area. To prevent this, a shore-side electrical power or cold-ironing facilities are starting to be introduced in recent years to allow the onboard DGs to be switched off when the vessels are at berth. The recent studies in [10–15] illustrate the concepts on the technical design aspect, challenges, and barrier of integrating shore-to-ship (S2S) power supply at the harbor area, and concluded that proper energy management strategies to balance load demand is the key to achieve a sustainable seaport. Technical challenges such as voltage and frequency synchronisation are elaborated in [12, 13] whereas safety aspects are elaborated in [14]. From the vessel operation, [15] discusses the importance of S2S in short-distance vessels. Furthermore, an overview of the ESS and time-shiftable loads are carefully presented in [7, 8], and concluded that they can significantly improve the seaport operation. Although time-shiftable loads can be scheduled effectively with the availability of the RESs, grid electricity price, and optimal loading condition of the distributed DGs, such research is yet to be explored. To the best of the authors’ knowledge, there is limited work done on designing an operational scheduling framework for the seaport microgrid aside from the ones that are discussed in [16–18]. However, [16] and [17] have yet to consider the potential for the integration of non-dispatchable RESs. [17] and [18] discuss the distributed fuzzy-logic-based seaport management and distribution design of the seaport microgrid with the grid and are just starting to highlight the complexity and necessity of such research.

Techniques to address the RESs uncertainty with robust optimisation in operation planning are highlighted in [19, 20]. However, its application to seaport microgrid especially on the coordinated operational scheduling in the day-ahead planning and hour-ahead generation scheduling is relatively limited in the literature. In most of the existing works, robust optimisation with a single associating objective is used to determine the unit commitment (UC) and dispatch level of the DGs and ESS units based on the worst-case uncertainty sets. With the large penetration of offshore RESs in seaport microgrid, the presence of the conflicting objectives (multi-objective) such as emission minimisation and profit maximisation requires the modification of the problem formulation. Hence, the proposed method aims to carry out day-ahead planning of the flexible load and UC of the distributed DGs based on the uncertainty sets while considering the conflicting objectives of the seaport operation. After the uncertainty realisation, dispatch decisions are carried out with the help of the day-ahead decision variables. In this sense, the proposed method segregates the longer-term planning decision variables from the shorter-term dispatch decision variables, and hence overall optimal planning and dispatch decisions can be achieved. With the planning of the flexible loads and unit commitments, the linearised distribution load flow analysis is required to ensure that the distribution network constraints are met at all the generation and load buses.

With the consideration of the research gaps, the main contributions of this work are highlighted. (1) A coordinated operational scheduling method of the seaport microgrid with the main grid and RESs is proposed. UC and time-shiftable load scheduling are coordinated with the optimal generation dispatch at different timescales (day-ahead and hour-ahead) to maximise the profit gain from transacting with the main grid while minimising the system operation cost and emission under uncertainties. The proposed method considers the seaport as an energy hub that transacts the power generated from the offshore RES and its distributed generation resources with the main grid which ensure the distribution network constraints. (2) Time-shiftable load scheduling is proposed which considers the RESs uncertainties and grid electricity pricing which is suitable for addressing the robust operation planning. (3) The proposed methods employed adaptive robust optimisation and linearised distributed load flow to address the uncertainties in RESs and to meet the distribution network constraints. Furthermore, to avoid over-conservativeness in UC in distributed DGs, conflicting or multi-objective functions (fuel, emission, and startup and shutdown cost of the distributed DGs versus profit gain from energy transaction back to the grid) are used as master and slave objectives formulation to determine the convergence criteria of the optimisation. (4) By utilising different time horizons and resolution at different stages, the proposed method improves the efficiency and accuracy of the dispatch result and is illustrated on the IEEE-33 bus distribution test system with a variety of uncertainty sets.

Coordinated operation framework and mathematical models of the seaport microgrid are proposed in Sections 2 and 3.
The solution method based on the two-stage adaptive robust optimisation is illustrated in Section 4. Case studies with the IEEE-33 bus distribution system with various sets of uncertainty as well as load uncertainty scenarios are detailed in Section 5. The conclusions and future works are detailed in Section 6.

2 | PROPOSED COORDINATED OPERATION PLANNING OF A SEAPORT MICROGRID

The traditional seaport relies heavily on the main grid supply capability and local distributed DGs to meet its load demand. Future seaport consists of RESs, ESS, and time-shiftable loads such as the S2S power supply system. RESs generate clean and low-cost electricity, ESS alleviates the energy management difficulties and schedulable loads ensure the power balance in the system. Generally, the objective is to optimise the operation cost, revenue, and reduce emission. Hence, this paper aims to propose a coordinated planning method to ensure the robustness and optimal operational scheduling of the seaport microgrid. Figure 1 shows the proposed coordinated operation planning framework for the seaport microgrid with RESs and S2S power supply systems. The proposed framework aims to address the uncertainties in RESs and coordinate the RESs, ESS, DGs, and main grid at the different timescales to minimise the operation cost and emission.

In this paper, it is assumed that local distributed DGs are the main source of power supply for the operation. Distributed DGs are reliable and dispatchable units that can supply the power deficit from the RESs, ESS, and the main grid to meet the load demand. The operation of the DGs is costly and required the burning of fossil fuel. The fuel consumption rate of the DGs depends on the specific fuel consumption characteristic and loading factor of the DGs. Starting and stopping the DGs require additional time and cost, and hence prior planning is required. Considering these characteristics, the DGs’ UC statuses are planned in a relatively longer timescale. In this study, DGs’ UC statuses are planned day-ahead with hourly intervals and within which the UC statuses of the DGs are fixed. These UC statuses of the DGs are considered as the first stage of the day-ahead operation planning. It is worthwhile to highlight that RESs outputs based on the initial weather forecast can be in a reasonably accurate interval and yet it can vary randomly within the forecast interval. Such random variation will deteriorate the optimal operation of the seaport and additional cost might incur. In worst-case scenarios, the operation limits of the seaport microgrid might be violated. Hence, the seaport microgrid operational scheduling should be planned to address the uncertainty present in the RESs. The second stage of day-ahead operation planning is designed to address the aforementioned problem. The aim of the second stage of day-ahead operational scheduling is to identify the worst-case uncertainty sets of the RESs and optimal solution set for the S2S load schedule. Thus, the first and second stages of day-ahead operation planning will be solved iteratively via two-stage robust optimisation until the potential worst-case scenario has been realised or the solution for the two stages converge. It must be noted that only the first-stage DGs’ UC decision variable and second-stage S2S load schedules are implemented in each hour for the following day.

Hour-ahead optimisation is carried out and implemented when the more accurate short lead-time RESs prediction data are available. In the hour-ahead operational scheduling, ESS and main grid contribution can respond to the changes in the system more quickly. Thus, higher time resolution optimal generation scheduling is carried out. It aims to modify the power dispatch level of the ESS, DGs, and main grid when the RESs outputs vary from the hour-ahead prediction values while minimising the operation cost and emission. In this study, it is assumed that the random variation in RESs lies within the interval of the day-ahead forecast intervals and hence will not modify the potential worst-case scenarios. Hence, further load shifting or shedding is not required with the UC decision of the DGs from the day-ahead operation planning. It should be highlighted that, although the dispatch results of the DGs, ESS, and grid from the day-ahead operation optimisation are not directly used in the hour-ahead operation optimisation, the UC and load schedules of the seaport operation are done based on the worst-case operating scenario and will have a strong influence on the way that these units are being operated in the hour-ahead scheduling. The optimal operation of these units is reconsidered in the hour-ahead operation optimisation by emphasising them in the objective formulation. Such a method of the formulation is required for the following reasons: (1) Presence of the uncertainty in the RESs forecasting; (2) Requirement for the fast-acting units such as ESS and the grid to make dispatch adjustment with fixed UC schedules of the fuel-dependent generation resources. Figure 1 is used to elaborate coordination between the decision variables at each stage of the operation planning.
3 | MATHEMATICAL MODELING

In this section, the proposed operational scheduling method for seaport microgrid is modelled mathematically. Optimal scheduling for S2S power demand and other important operation constraints are also illustrated in detail.

3.1 | Local distributed generators model

DGs are the main source of power supply in the proposed seaport microgrid. It is used to supply the load demand when the power supply from the ESS, wind, and photovoltaic (PV) is insufficient. The fuel consumption characteristic of the DGs depends on the loading condition of the DGs which is illustrated in (1). The UC of the DGs must be planned carefully in power system operation to avoid excessive starting and stopping, and sub-optimal loading of the DGs that might lead to unnecessary fuel consumption. The UC of the DGs should also cater to the worst-case scenarios to ensure system generation reliability. Furthermore, due to the longer thermal time constant of the DGs, the operation planning of the DGs cannot be considered as a ‘here-and-now’ decision, unlike other energy sources. As a result, it has to be planned day-ahead of the actual operation.

\[
F_{DG,n} \approx a_n \cdot (P_{n\,DG})^2 + b_n \cdot P_{n\,DG}. \tag{1}\]

3.2 | Shore-to-ship power demand scheduling model

In this study, a profit-driven S2S logistic planning is derived. The total load of seaport microgrid can be divided into essential and time-shiftable S2S loads. The essential load requirement has to be fulfilled as necessary whereas time-shiftable S2S load demand can be scheduled based on the grid electricity price, availability of generation sources, and RESs to decrease the overall system operating cost. The vessels with long berthing duration can provide the flexibility in scheduling the shore power demand by shifting their load demand to more economic operating hours. In this study, it should be noted that the shore power demand of the vessels which cannot be scheduled are incorporated into the essential loads and the S2S power supply capability \(P_{S2S,\text{max}/\text{min}}\) is adjusted. The S2S logistic planning is modelled as follows. The ratio of time-shiftable S2S power demand with the total load demand is represented in (2). The essential load demands are computed as shown in (3).

\[
K_{S2S} = \frac{P_{S2S,0}}{P_{\text{total}}}, \tag{2}\]

\[
P_{\text{est}} = (1 - K_{S2S})P_{\text{total}}. \tag{3}\]

Time-shiftable S2S power demand is re-scheduled based on the initial demand values \(P_{S2S,0}\) which are based on the expected number of vessels at berth. In this study, it will be assumed that the expected number of vessels at berth is known and used to design the bounds for the S2S power adjustment. The time-shiftable S2S constraints are illustrated in (4) and (5). With the assumption that the power factor for the S2S power demand is fixed, the reactive power demand is formulated as shown in (6) and (7). It should be highlighted that other schedulable loads of the seaport microgrids such as winch and quay cranes are also considered as time-shiftable load and hence separate models are not illustrated. Since the focus of this study is to optimally schedule the electrical loads and explore seaport microgrid as an electrical energy hub with high renewable, optimal scheduling of thermal networks such as refrigerated containers (reefers), combined cooling and heating load requirements are assumed to have been incorporated into the total electrical load demand of the system.

\[
P_{S2S,\text{min}} \leq P_{S2S} \leq P_{S2S,\text{max}}, \forall t, \tag{4}\]

\[
\sum_{t=1}^{T} P_{S2S,0}(t) = \sum_{t=1}^{T} P_{S2S}(t), \tag{5}\]

\[
Q_{S2S,\text{min}} \leq Q_{S2S} \leq Q_{S2S,\text{max}}, \forall t, \tag{6}\]

\[
\sum_{t=1}^{T} Q_{S2S,0}(t) = \sum_{t=1}^{T} Q_{S2S}(t). \tag{7}\]

3.3 | Seaport microgrid operation model

In this study, the objective of the optimisation is to minimise the cost of operation while reducing the emission of the seaport microgrid. It comprises the cost of the fuel, cost or revenue incurred from the power exchange with the grid, cost of carbon emission, as well as the cost of operation of the DGs, ESS, and RESs. Hence, the overall objective function of the optimisation problem is illustrated in (8).

\[
\min \text{ cost}_{\text{fuel}} + \text{ cost}_{\text{SU/SD}} + \text{ cost}_{\text{max,}DG} + \text{ cost}_{\text{grid}} + \text{ cost}_{\text{emission}} + \text{ cost}_{\text{ESS}} + \text{ cost}_{\text{PV}} + \text{ cost}_{\text{wind}} \tag{8}\]

The cost and revenue calculation functions in the objective function (8) are illustrated in (9–16), that is, fuel consumption cost, operation and maintenance cost of the DGs, PV and wind turbines, startup/shutdown cost of the DGs, transaction cost or revenue with the grid, emission cost and finally the cost and revenue obtained from the ESS operation. ESS operation constraints are illustrated in (17–20). Depth of discharge and storage capacity of the ESS are computed with (17) and (18). Minimum and maximum charging/discharging constraints of the ESS are illustrated in (19) and (20).Constraint (21) describes the first-stage UC decision variables. The DGs’ operation constraints, minimum/maximum loading factor, ramp rate, and minimum up/downtime duration, are illustrated in (22–24).
Constraint (25) limits the minimum/maximum power exchange between the main grid and the seaport microgrid. Constraints (26) and (27) illustrate the stochasticity of the RESs which can vary within the range of the forecast interval. Constraints (28–31) are linearised distribution load flow equations. It should be noted that power distribution losses are not considered in this study for two reasons: (1) cost associated with it is significantly smaller than the other terms in the objective function; (2) introduction of the non-linear term will further complicate the solving of the optimisation problem. Equations (9–31) represent the overall mixed-integer programming problem of the seaport microgrid with the uncertain variables.

\[
s \cdot t \cdot \text{cost}_{\text{fuel}} = \sum_{i=1}^{T} \sum_{n=1}^{N} F_{\text{fuel}} \times \Delta t \times FC_{DG,N}(t),
\]

\[
\text{cost}_{SU/SD} = \sum_{i=1}^{T} \sum_{n=1}^{N} |u_{DG}(t) - u_{DG}(t+1)| \times F_{\text{transition}}
\]

\[
\text{cost}_{\text{fuel, DG}} = \Delta t \times \sum_{i=1}^{T} \sum_{n=1}^{N} F_{DG,\text{fuel}} \times P_{DG}(t),
\]

\[
\text{cost}_{\text{grid}} = \Delta t \times \sum_{i=1}^{T} P_{\text{grid}}(t) \times F_{\text{ele}}(t),
\]

\[
\text{cost}_{\text{emission}} = \Delta t \times \sum_{i=1}^{T} F_{\text{CO}_2} \times \Delta t \times FC_{DG,N}(t),
\]

\[
\text{cost}_{\text{ESS}} = \sum_{i=1}^{T} [P_{\text{dis}}(t) - P_{\text{ch}}(t)] \times F_{\text{ele}}(t),
\]

\[
\text{cost}_{\text{pe}} = F_{\text{pe, main}} \times \sum_{i=1}^{T} \frac{P_{\text{pe}}(t)}{\Delta t},
\]

\[
\text{cost}_{\text{w}} = F_{\text{w, main}} \times \sum_{i=1}^{T} \frac{P_{\text{w}}(t)}{\Delta t},
\]

\[
\text{SOC}_{\text{min}} \leq \text{SOC}(t) \leq \text{SOC}_{\text{max}},
\]

\[
\text{SOC}(t) = \text{SOC}(t-1) + \frac{[\eta_{\text{ch}} \times P_{\text{ch}}(t) \times \Delta t] \times \Delta t}{E_{\text{ESS, rated}}} \times 100,
\]

\[
P_{\text{ch, min}} \cdot \eta_{\text{ESS}}(t) \leq P_{\text{ch}}(t) \leq P_{\text{ch, max}} \cdot \eta_{\text{ESS}}(t),
\]

\[
P_{\text{dis, min}} \cdot \eta_{\text{ESS}}(t) \leq P_{\text{dis}}(t) \leq P_{\text{dis, max}} \cdot \eta_{\text{ESS}}(t),
\]

\[
\eta_{DG}(t) \in \{0, 1\}, \forall t, N,
\]

\[
P_{DG_{\text{min}}} \leq P_{DG}(t) \leq P_{DG_{\text{max}}},
\]

\[
\left| \frac{P_{DG}(t) - P_{DG}(t-1)}{\Delta t} \right| \leq P_{DG_{\text{ramp}}},
\]

\[
U_{DG_{\text{on-off}}} - U_{DG_{\text{off-on}}} \geq U_{DG_{\text{min}}},
\]

\[
\eta_{\text{grid}}(t) \cdot P_{\text{grid, min}} \leq P_{\text{grid}}(t) \leq \eta_{\text{grid}}(t) \cdot P_{\text{grid, max}},
\]

\[
P_{\text{pe, min}}(t) \leq P_{\text{pe}}(t) \leq P_{\text{pe, max}}(t), \forall t,
\]

\[
P_{\text{w, min}}(t) \leq P_{\text{w}}(t) \leq P_{\text{w, max}}(t), \forall t,
\]

\[
P_{DG+1}(t) = P_{DG}(t) - P_{DG_{\text{on-off}}}(t) + P_{DG_{\text{on-off}}}(t),
\]

\[
Q_{DG+1}(t) = Q_{DG}(t) - Q_{DG_{\text{on-off}}}(t) - Q_{DG_{\text{on-off}}}(t),
\]

\[
V_{\text{min}}(t) \leq V(t) \leq V_{\text{max}}(t).
\]

## 4. SOLUTION METHOD

The uncertainty present in the RESs will have a significant effect on system performance. Hence, this study proposes a two-stage adaptive robust optimisation method where the uncertainty present in the RESs is modelled as uncertainty sets. The first-stage decision variables are optimised for the worst-case uncertainty sets which are obtained from the second stage. This is to ensure that the final solution obtained is robust against the worst-case uncertainty sets while meeting the operating constraints. The two stages will solve iteratively until the solution converges.

### 4.1. Uncertainty modelling

To generate a robust optimal solution for the proposed problem, the uncertain variables are searched from the given uncertainty set to form the worst-case scenario with the highest
operating cost. The uncertainty sets for the PV and wind power can be formulated as illustrated in (32) and (33). For the given uncertainty set, the uncertainty variables can vary randomly within the uncertainty bounds. The uncertainty bounds can be further modified by adjusting the uncertainty budget of the set. The budget of the uncertainty set can be represented as shown in (34) and (35). The larger uncertainty budget for a given interval prediction data set will result in a more robust solution and the smaller uncertainty budget will result in a risk-taking solution. As a result, the design of the uncertainty budget will determine the trade-off between the robustness and conservativeness of the solution.

\[
U_{PV} : P_{PV,\min}(t) \leq P_{PV}(t) \leq P_{PV,\max}(t), \\
\sum_{t=1}^{T} P_{PV}(t) \leq \bar{\mu}_{PV}, \forall t, P_{PV}(t) \in \mathbb{R}, \\
U_{w} : P_{w,\min}(t) \leq P_{w}(t) \leq P_{w,\max}(t), \\
\sum_{t=1}^{T} P_{w}(t) \leq \bar{\mu}_{w}, \forall t, P_{w}(t) \in \mathbb{R}, \\
0 \leq \Gamma_{PV}(t) \Gamma_{w}(t) \leq 1, \forall t, \\
0 \leq \sum_{x=1}^{n_{unc}} \Gamma_{x}(t) \leq n_{unc}. 
\]

### 4.2 Solution to day-ahead operation

In the model, decision variables are classified into two categories; ‘day-ahead here-and-now’ and ‘hour-ahead wait-and-see’ solution sets. The day-ahead planning decisions are made before the uncertainty realisation or with the imperfect information of the system operation while the hour-ahead decisions are further carried out to improve the optimal operating point of the system when the uncertainties are realised. Hence, the day-ahead decision variables are referred to as here-and-now solutions whereas the hour-ahead decisions are referred to as wait-and-see solutions. It should be highlighted that these two types of decision variables are strongly coupled in the optimisation model by incorporating the day-ahead here-and-now decision variables into the hour-ahead optimisation to identify the wait-and-see decision variables. Hence, although the dispatch results of the DGs, ESS, and grid from the day-ahead operation optimisation are not directly used in the hour-ahead operation optimisation, the UC and load schedules of the seaport operation which are designed for the worst-case scenario will be incorporated into the hour-ahead optimisation model to further improve the wait-and-see decision variables. Since the here-and-now decisions are carried out for the worst-case scenario, the optimality of the seaport operation will tend to improve with the hour-ahead dispatch adjustment. The day-ahead operation planning of the seaport microgrid is represented as a robust optimisation model as shown in (36).

\[
\min_{x} \text{cost}_{\text{fuel}} + \text{cost}_{\text{SU/SD}} + \text{cost}_{\text{DG}} + \text{cost}_{\text{emission}} \\
\quad + \max_{\bar{P}_{PV}, \bar{P}_{w}, \bar{P}_{grid}} \min_{\under{\text{here-and-now decision variables}}_{x}} \text{cost}_{\text{grid}} + \text{cost}_{\text{ESS}} + \text{cost}_{\text{PV}} + \text{cost}_{\text{wind}} 
\]

To solve two-stage robust optimisation problems, Bender’s decomposition method and column and constraints generation algorithms (C&CG) are widely used. However, as a result of the faster convergence, the C&CG method is employed in this study. In C&CG, the problem is divided into a master and slave problem. In the master problem, the first-stage problem is solved with the worst-case uncertainty set. In the slave problem, the max–min problem is solved to identify the worst-case uncertainty sets for the RESs. The master and slave problems are solved iteratively until the termination value is achieved. The master problem will provide lower bound and the slave problem will provide an upper bound of the solution. The difference between the upper and the lower bound is the convergence criteria for the C&CG. The compact form of the master problem is expressed in (37–41). The constraints (21–24) for the master problem is grouped into (38).

\[
\min_{x} \epsilon^T x + \lambda, \\
s \cdot t \cdot Ax \geq b, \\
\lambda \geq d^T y + e^T u^*, \\
F x + G y + H u^* \leq v, \\
I(u^*) x + J y + K u^* = w, u^* \in \mathcal{U}. 
\]

For the proposed optimisation framework, \( x \) is a set of DGs’ UC binary decision variables whereas \( y \) is the loading factor of the S2S power supply. With the uncertainty variables identified from the slave problem, an optimal solution \( (x^*, \lambda^*) \) can be obtained for the master problem. \( x^* \) is the current optimal solution and it will be used further to solve the slave problem. The compact form of the slave problem can be expressed as shown in (42–44).

\[
S(u, x^*) = \min_{x^*} \max_{y} d^T y + e^T u, \\
s \cdot t \cdot F x^* + G y + H u \leq v, \\
I(u)x^* + Jy + Ku = w, u \in \mathcal{U}. 
\]
For simplicity, the max–min problem in this study is treated as a bilevel problem. It should be noted that the DGs’ UC outputs and load adjustment of the S2S logistic planning from the first stage of the day-ahead operation planning will be realised whereas the dispatch levels of the system will be re-evaluated with the availability of shorter-leading time prediction data during the hour-ahead dispatch.

### 4.3 Solution to hour-ahead operation

With the shorter lead time, uncertainty in the RESs are realised, and a deterministic optimisation approach can be adopted. For hour-ahead operational scheduling, the objective function can be illustrated as shown in (45).

\[
\begin{align*}
\min_{P, Q, V} & \quad \text{cost}_{\text{fuel}} + \text{cost}_{\text{emission}} + \text{cost}_{\text{grid}} \\
& + \text{cost}_{\text{mai,DG}} + \text{cost}_{\text{ESS}} + \text{cost}_{\text{PV}} + \text{cost}_{\text{wind}}.
\end{align*}
\]

(45)

In this optimisation with a shorter lead time, the dispatch level of the DGs unit, ESS and grid are determined with the more accurate hour-ahead forecast of the RESs at a higher time resolution. The UC decision of the DGs and S2S power demand are the parameters of the optimisation which is obtained from the hour-ahead operational scheduling. As the UC of the DGs is carried out under the potential worst-case scenario, the solution to hour-ahead operational scheduling can ensure a robust solution while satisfying the operating constraint of the system.

### 5 CASE STUDY

#### 5.1 Test system and simulation setup

To demonstrate the proposed operation planning framework, the IEEE-33 bus radial distribution system is modified and used. The modified system topology is illustrated in Figure 2 and the distribution network data are obtained from [21]. The voltage level at the point of common coupling (PCC) with the main grid is taken to be 12.66 kV and the maximum allowable voltage deviation is taken to be 0.1 p.u. from the nominal bus voltage. The rated power and energy data for the DGs, ESS, PV, and wind turbines are provided in Table 1. For the ease of illustration and without losing the generality, the loads are aggregated into different bus locations as shown in Figure 2. Moreover, the optimal placement of the generation sources and loads are out of the scope of this paper will not be addressed in this study. However, the case study will have to ensure that the bus voltage variations are within the specified limits to meet the system distribution constraints. The other parameters used for the seaport microgrid operation constraints formulation are given in Tables 2 and 3.

The lower and upper bounds of the interval prediction data of the RESs are set at 0.8 and 1.2 of the expected mean value of the PV and wind power outputs, and they are illustrated as shown in Figure 3. The proposed coordinated planning framework is tested with various uncertainty budget for the PV and wind power outputs. The electricity transaction price with the main grid, essential load, and the initial schedule of time-shiftable S2S loads are illustrated in Figure 4. The simulation is carried out on a 64-bit PC with 3.30Ghz CPU and 16 GB RAM. Yalmip [23] is used for the mathematical programming in MATLAB and CPLEX solver is used to solve the optimisation [24].

### Table 1 Parameters for DGs, ESS, PV, and wind generation resources

| Node | Type | Rated stored energy (kWh) | Rated power (kW) |
|------|------|---------------------------|-----------------|
| 6    | DG1  | —                         | 3350            |
| 6    | DG2  | —                         | 2750            |
| 18,24| ESS  | 1500                      | 500             |
| 18,24| Wind | —                         | 1800            |

### Table 2 Diesel generator parameters

| Parameter | Value |
|-----------|-------|
| $P_{1,DG}^{\min}$ | 850 kW |
| $P_{1,DG}^{\max}$ | 3350 kW |
| $U_{1,DG}^{\min}$ | 1 h |
| $U_{1,DG}^{\max}$ | 1 h |
| $P_{1/2,DG}^{\text{tramp}}$ | 1000 kW |
| $c_{a}$ | 2.68 kg/litres |
| $a_1 = 1.426 \times 10^{-6}$ | |
| $a_2 = 1.16 \times 10^{-6}$ | |
| $b_1 = 0.2216$ | |
| $b_2 = 0.2199$ | |
| $F_\text{fuel}$ | 0.83 $/\text{litres}$ |
| $F_\text{DG,mai}$ | 0.005 $/\text{kWh}$ |
| $F_\text{transition}$ | 10 $/\text{transition}$ |
| $F_{\text{CO}_2}$ | 30 $/\text{ton}$ |

### Table 3 Energy storage and grid parameters

| Parameter | Value |
|-----------|-------|
| $SOC_{\text{min}}$ | 20% |
| $SOC_{\text{max}}$ | 80% |
| $P_{\text{ch/disch min}}$ | 0 kW |
| $P_{\text{ch/disch max}}$ | ±500 kW |
| $\eta_{\text{disch}}$ | 97% |
| $P_{\text{grid,min/max}}$ | ±1000 kW |
5.2 | Day-ahead operation result

5.2.1 | With uncertainty in load forecasting

In this section, the influence of the uncertainty in load forecasting (essential and time-shiftable S2S load) on the UC of the DGs are discussed. With the assumption that there is an uncertainty in load forecasting, the flexibility provided by the time-shiftable load should be handled more efficiently. If the model assumed an uncertainty in load forecasting, the proposed two-stage robust model is modified as shown in (46). The lower and upper limits of the renewable generation uncertainty is taken as ±10% and for the essential and time-shiftable loads are taken as ±20% from their nominal forecast values. Furthermore, the amount of load-shifting modelled in (4–7) are further bounded based on the lower and upper limit of the time-shiftable load uncertainty budget. The UC results for the modified model is illustrated in Table 4. The worst-case uncertainty sets for the RESs generation as well as the essential and time-shiftable loads data are illustrated as shown in Figures 5 and 6. The total operating cost of the seaport microgrid under the worst-case uncertainty set is $8496.6 and the slave problem is $–5649.6. In this case, it should be highlighted that with uncertainty in essential and flexible load, the UC of the DGs are committed to a higher extent based on the worst-case uncertainty of the load demand. Hence, it has resulted in higher amount of energy to be transacted back to the grid while evaluating the slave problem in the two-stage robust model. With the higher uncertainty budget in the load, the more DGs are committed as it is strongly coupled to the power balance equation as described in (28).

\[
\min \text{cost}\_{\text{fuel}} + \text{cost}_{\text{SU}/\text{SD}} + \text{cost}_{\text{mai},\text{DG}} + \text{cost}_{\text{emission}} + \max_{P_{\text{PV}},P_{\text{w}},P_{\text{est}},P_{\text{S2S}} \leq 0.1} \text{cost}_{\text{grid}} + \text{cost}_{\text{S2S}} + \text{cost}_{\text{PV}} + \text{cost}_{\text{wind}},
\]

(46)

TABLE 4  Diesel generators unit commitment results of master problem with load uncertainties

| Time (h) | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  |
|----------|----|----|----|----|----|----|----|----|
| DG unit 1 | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  |
| DG unit 2 | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  |

| Time (h) | 9  | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|----------|----|----|----|----|----|----|----|----|
| DG unit 1 | 1  | 1  | 1  | 1  | 0  | 0  | 0  | 0  |
| DG unit 2 | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  |

| Time (h) | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|----------|----|----|----|----|----|----|----|----|
| DG unit 1 | 0  | 0  | 0  | 0  | 0  | 0  | 0  | 0  |
| DG unit 2 | 1  | 1  | 1  | 1  | 1  | 1  | 1  | 1  |

Note: ‘On’ and ‘Off’ status of the diesel generator units are represented by the binary coefficients 1 and 0.
In this study, the S2S power demands are based on the historical operating data of the Port of Oakland as shown in Figure 4. Hence, the two-stage robust optimisation assumed that the total load demand (time-shiftable and essential load demands) are predicted accurately and any uncertainty in load forecasting can be efficiently addressed by the dispatch adjustment of the generation units or the grid. Hence, the proposed work focuses on addressing the uncertainty present in the RESs for the following reasons: (1) RESs have a higher level of uncertainty in forecasting as compared to the total electrical load demand of the seaport microgrid. The essential and time-shiftable loads are also scheduled and fixed a day-ahead of the actual operation. (2) The port or system operators have no control over the amount of RESs but on the other hand, they have a certain level of control over the total electrical load demand (shedding or re-scheduling of non-essential loads) with efficient scheduling. (3) Consideration of too many uncertainty variables in the day-ahead model will result in an overly conservative results that might cause the UC decisions to be far away from their optimality. Hence, in the subsequent sections, the essential and time-shiftable load uncertainties are assumed to be realised.

5.2.2 With reliable load forecasting

With the uncertainty set model developed in Section 4.1, the proposed two-stage robust optimisation illustrated in Section 4.2 is solved for the day-ahead operation planning with C&CG. The worst-case scenario for the RESs with the uncertainty budget of ±10% (test case 1) is illustrated in Figure 7 for a given uncertainty interval. It is found by maximising the minimisation of the second stage of the robust optimisation as illustrated in (42–44). It is noted that for the given uncertainty range, the worst-case uncertainty set might not always lie in the boundary condition of the given uncertainty budgets. The intermediate objective values of the two-stage robust optimisation are illustrated in Table 5 for test case 1. The sub-problem or the slave problem in the robust optimisation is negative as the system tries to maximise the profit or minimise the cost from selling electricity back to the main grid for a given uncertainty set. The total operating cost of the DGs in the seaport microgrid optimisation at the worst-case scenario for the first test case is $8921.3.

To have a better understanding of the day-ahead robust optimisation, the dispatch results of the generation and storage units are illustrated in Figure 8. The updated scheduling of the time-shiftable S2S load is also illustrated in Figure 8. It should be highlighted that S2S load demands are shifted based on the grid electricity price, RESs generation, and overall load demand of the system. As a result, it is observed that most of the time-shiftable loads are shifted to time instances when the load demand is low or when the DGs are sub-optimally loaded. Furthermore, ESS complements the system operation by charging when the RES generation is high and when the grid electricity price is low. ESS is mainly discharged in time instances (1st–4th and 20th–22nd hours) when the amount of RESs are smaller and charges in time instances (14th–16th hours) when the RESs energy output exceeded the total load demand. Furthermore, when the grid electricity price is high, ESS will discharge to either provide the load or sell the stored energy back to the grid. It is also observed that DGs units are switched off during the 15th and 16th hours and time-shiftable loads are re-scheduled to other time instances so as to minimise the cost of running the DGs. As a result, most of the energy generated is sold back to the grid at 1st to 4th hour, 9th to 11th hour, and 20th to 24th hour of the seaport operation. Hence, it can be concluded that the optimal scheduling of seaport microgrid not only provides additional flexibility in the system operation to optimise the operation cost but also to achieve economic benefit. However, the dispatch results in Figure 8, and the cost represented in test case 1 is for the worst-case scenario. In hour-ahead dispatch, dispatch adjustment can be carried out to further reduce the cost of operation. However, only the DGs’ UC results in Table 6 and the time-shiftable S2S load scheduling data in Figure 8 is implemented for day-ahead operation planning. The generation dispatch data will be re-evaluated in the hour-ahead

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**Table 5** Objective functions for the two-stage robust optimisation

| Iteration | Master problem objective value ($) | Slave problem objective value ($) |
|-----------|-----------------------------------|----------------------------------|
| 1         | 8226.3                            | -3861.7                          |
| 2         | 8921.4                            | -3815.7                          |
| 3         | 8921.3                            | -3815.7                          |
TABLE 6  Diesel generators unit commitment results of master problem for test no 1

| Time (h) | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|----------|---|---|---|---|---|---|---|---|
| DG unit 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| DG unit 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

| Time (h) | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|----------|---|----|----|----|----|----|----|----|
| DG unit 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| DG unit 2 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |

| Time (h) | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|----------|----|----|----|----|----|----|----|----|
| DG unit 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| DG unit 2 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |

Note: ‘On’ and ‘Off’ status of the diesel generator units are represented by the binary coefficient 1 and 0.

TABLE 7  Objective functions for the two-stage robust optimisation

| Test No | Wind | PV | Worst-case objective ($) | Iteration |
|---------|------|----|--------------------------|-----------|
|         | $\mu_{wind,l}$ | $\mu_{wind,u}$ | $\mu_{PV,l}$ | $\mu_{PV,u}$ |                      |           |
| 1        | 0.9  | 1.1 | 0.9 | 1.1 | 8921.3 | 3 |
| 2        | 0.85 | 1.15 | 0.85 | 1.15 | 9079 | 3 |
| 3        | 0.8  | 1.15 | 0.8 | 1.15 | 9248.4 | 4 |

scheduling to improve the accuracy and reliability of the generation dispatch.

In addition, to demonstrate the influence of the uncertainty budget on the robust optimisation, the same test system is reevaluated with three different sets of uncertainty budgets. The impact of uncertainty budget on the objective functions are illustrated in Table 7. One general observation is that, with the increase in the uncertainty budget, the more number of DG units are being committed. This is to address the higher uncertainty in the RES generation. With the increase in the uncertainty budget, it will also take a larger number of iteration for the two-stage robust optimisation solution to converge.

5.3  Hour-ahead operation result

For hour-ahead prediction data for the PV and wind power generation, the uncertainties are assumed to be realised. A single objective function which optimises the trade-off between the emission from the DGs and other operating cost and benefit as shown in (45) is re-optimised for a higher time resolution with more accurate point forecast data and the results obtained from the day-ahead operational scheduling.

The optimisation is carried out for a shorter time horizon with higher time resolution and thus allowing the RESs data to be constantly updated. Without losing the generality, the generation dispatch results from 8th to the 15th hour is illustrated with the time step of 15 min in Figure 9. The worst-case uncertainty sets and the updated forecast data are also illustrated in Figure 9. The objective value of the above-mentioned time horizon is $2778.76 which is improved from the $2807.08 of the day-ahead robust optimisation. It indicates that the actual operating cost of the system is lower than the worst-case scenario which is identified in the day-ahead operational scheduling when the actual RESs outputs are different from the worst-case sets. Furthermore, it has also proved that the UC decisions are able to address the deviation from the initial forecast of the worst-case uncertainty set. In addition, higher time resolution hour-ahead dispatch will greatly benefit the seaport microgrid operator to have a better understanding of the energy transaction with the grid, making adjustments quickly to achieve a better economic benefit. As for example, dispatch adjustments with the grid are carried out quickly between 10th to 14th hour. Similar quick dispatch adjustments are also observed for the DGs and ESS. Hence, it is concluded that the solution obtained from the hour-ahead scheduling could be used to improve the performance of seaport microgrid operation.

Generally, a robust optimisation approach tends to be conservative in nature to ensure the reliability of the dispatch solution. The study not only proves that using it alone to carry out operational scheduling of the seaport microgrid might result in a conservative solution. However, the proposed coordinated operational scheduling and generation dispatch optimisation proved that the dispatch adjustment can be done at higher time resolution to minimise the conservativeness of the day-ahead operational scheduling while ensuring the dispatch and distribution reliability for a microgrid with high RESs penetration.

6  CONCLUSION

This paper proposed a robust coordinated operational scheduling framework for seaport microgrid which addresses the uncertainty present in RESs forecasting and time-shiftable load scheduling of the S2S power demand. Unlike a grid-supported microgrid, the seaport microgrid operator wants to minimise the energy demand from the grid while encouraging the selling of the excess energy back to the main grid for economic benefit. In the proposed framework, UC status of the DGs and load scheduling of time-shiftable S2S loads are determined.
day-ahead of the operation with the robust optimisation approach. The results are used to carry out economic dispatch in the hour-ahead scheduling to minimise the cost of operation and emission. To strengthen the proposed solution, day-ahead and hour-ahead optimisation are carried out with different time horizons and resolution at different stages of the scheduling. The overall objective of the coordinated framework is to minimise the cost of operation of the system while attempting to reduce the emission with the help of the RESs, distributed ESS, and grid support. The proposed framework is demonstrated on the modified IEEE-33 bus system. The test result indicates the proposed solution is efficient and ensured good robustness in the coordinated operational scheduling of seaport microgrid. Furthermore, the case illustration also demonstrated the potential for the seaport microgrid as an interface between the RESs and the main grid. In the future, the model can be improved to incorporate the multi-energy carriers such as heating and cooling systems of the seaport microgrid as well as detailed analysis on the main grid electricity pricing schemes on the operation of seaport.

**NOMENCLATURE**

**Input Parameters**

- $a_n$, $b_n$: $n$th DG fuel consumption parameters
- $c_{\text{CO}_2}$: Carbon conversion factor
- $E_{\text{ESS, rated}}$: Rated energy of the ESS
- $F_{\text{fuel}}$: Per unit cost of fuel
- $F_{\text{transition}}$: Cost of DGs transition of state
- $F_{\text{DG, mai}}$: Maintenance cost of DGs
- $F_{\text{ele}}$: Per unit cost of electricity (time of use)
- $F_{\text{PV, mai}}$: Maintenance cost of PV
- $F_{\text{wind, mai}}$: Maintenance cost of wind turbines
- $K_{\text{S2S}}$: Percentage of time-shiftable load
- $n_{\text{unc}}$: Number of uncertain variables
- $P_{\text{DG, ramp}}$: Maximum ramp rate limit
- $P_{\text{est}}$: Essential load
- $P_{\text{total}}$: Total load demand
- $\Delta t$: Optimisation time step
- $U_{\text{n,DG, min}}$: Minimum on/off duration of $n$th DG
- $\eta_{\text{ch/ds}}$: Charge and discharge efficiency of ESS
- $\mu/\mu_{\text{ch/ds}}$: Limits of the uncertainty variables

**Variable**

- $\text{cost}_{\text{fuel}}$: Total cost of fuel
- $\text{cost}_{\text{PV}}$: Total cost of PV operation
- $\text{cost}_{\text{wind}}$: Total cost of wind turbine operation
- $\text{cost}_{\text{SU, SD}}$: Total cost of startup and shut down of DGs
- $\text{cost}_{\text{DG, mai}}$: Total cost of maintenance of the DGs
- $\text{cost}_{\text{grid}}$: Total cost of power exchange with the grid
- $\text{cost}_{\text{emission}}$: Total cost of emission from the seaport
- $\text{cost}_{\text{ESS}}$: Total cost of operation of ESS
- $F_{C_{\text{DG, n}}}$: Fuel consumption of $n$th generator
- $P_{\text{DG, n}}$: Power output of $n$th generator
- $P_{\text{PV}}$: Power generation of PV
- $P_{\text{wind}}$: Power generation of wind turbine
- $P_{\text{grid}}$: Power exchange at PCC with the main grid
- $P_{\text{ch}}$: Charge power requirement from ESS
- $P_{\text{dis}}$: Discharge power requirement from ESS
- $P/Q_{\text{S2S}}$: Active and reactive shore power demand
- $\text{SOC}$: State of Charge of the ESS
- $U_{\text{n,DG, on/off}}$: Time instance of $n$th DG switching off
- $U_{\text{n,DG, off-on}}$: Time instance of $n$th DG switching on
- $u_{\text{n,DG}}$: On/off generator status (binary)
- $r_{\text{grid}}$: Grid connection status (binary)
- $w_{\text{ESS}}$: ESS operation status (binary)
- $\Gamma$: Uncertainty budget

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