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Energy Management Strategy of a Green Port Serving Emission-Free Ferries Considering EV Parking Lot Availability

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Abstract—While the role of transportation is indispensable in daily life, the transportation sector is one of the major contributors to greenhouse gas (GHG) emissions. With the utilization of green vehicles in transportation systems and the adoption of renewable energy sources in power systems, it becomes possible to achieve an environmentally friendly transportation system. In this paper, an energy management algorithm for a port power system is presented, including a solar-based local power production unit serving hybrid ferries having fuel cell/battery, as well as an electric vehicle (EV) parking lot, allowing for bi-directional power flow between the port and the grid. The proposed concept enables dual integrated green transportation with the possibility of parking EVs to the lot and then continuing to journey via another green transportation option. The stochasticity regarding the photovoltaic plant (PVP) and EV behaviors are taken into consideration under a real-time rolling horizon optimization framework. Minimizing the operational cost of the port related to the energy consumption is the objective function in this novel transportation-to-transportation integration concept. Numerous case studies have been developed and tested to demonstrate the effectiveness of the suggested algorithm.

Index Terms—Energy management, green ports, fuel cell/battery hybrid system, parking lot management system, real-time optimization, rolling optimization, zero emission ferries.

NOMENCLATURE

Tables A to D indicate the notation used throughout this work in detail. It ought to be noted that all variables have positive values, and this condition is not shown on an individual basis.

A. ABBREVIATIONS

EV	Electric vehicle.
GHG	Greenhouse gas.
G2P	Grid to the port.
GTL	Grid transaction limit.
PVP	Photovoltaic plant.
P2G	Port to the grid.
SoE	State of energy.

B. SETS AND INDICES

$card()$	Cardinality of a set.
h	Executed optimization round.
k	EV set
n	Ferry set
t	Time set

C. PARAMETERS

CE_n^F	Charging efficiency of the battery of ferry n .
CR_n^F	Charging rate of the battery of ferry n .
DE_n^F	Discharging efficiency of the battery of ferry n .
DR_n^F	Discharging rate of the battery of ferry n .
K_1	Constant parameter for electrolyzer [kg/kWh]
$K_{2,n}$	Constant parameter for the fuel cell of the ferry to define the required amount of power to produce hydrogen [kg/kWh].

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$K_{3,n}$	The power rate from the battery to ferry n in berthed-out mode.
$\lim^{P_{ELC}}$	Electrolyzer power limit [kW].
$\lim^{m^{H,P2F}}$	Hydrogen transaction limit from the port storage unit to the ferries' tank [kg].
$m_n^{H,CapF}$	Capacity of the hydrogen tank of the ferry n [kg].
$m^{H,CapP}$	Capacity of the hydrogen tank of the port [kg].
$m_n^{H,desF}$	Desired hydrogen level for ferry n [kg].
$m_n^{H,F_{init}}$	The initial hydrogen level in storage tank of ferry n [kg].
$m_{n,t}^{H,FC2F_{b-out}}$	The consumed hydrogen amount by the fuel cell of ferry n in berthed-out mode in period t [kg].
$m^{H,StoreP-init}$	The initial amount of hydrogen in storage unit of the port [kg].
$m^{H,StoreP-min}$	The minimum hydrogen level of the port storage unit [kg].
GTL	Grid transaction limit [kW].
$P_{n,t}^{Dchar_{b-out}}$	Maximum discharging power of the battery of the ferry n in berthed-out mode in period t [kW].
$P_{n,t}^{FC2F_{b-out}}$	Power from fuel cell of ferry n in berthed-out mode in period t [kW].
$P_{h,t}^{PVP}$	The power generation of PVP in period t [kW].
$P_{n,t}^{Sail}$	Power demand of ferry n in berthed-out mode in period t [kW].
$P_{n,t}^{Serv}$	Power requirement of the ferry n in berthed-in mode in period t [kW].
$SoE_k^{bat_{cap},EV}$	Maximum SoE of the battery of EV k [kWh].
$SoE_n^{bat_{cap},F}$	Maximum SoE of the battery of ferry n [kWh].
$SoE_k^{bat_{des},EV}$	Desired SoE of EV k [kWh].
$SoE_n^{bat_{des},F}$	Desired SoE of ferry n [kWh].
$SoE_k^{bat_{init},EV}$	Initial SoE of EV k [kWh].
$SoE_{k/n}^{bat_{min},EV/F}$	Minimum SoE of the battery of EV k / ferry n [kWh].
$T_{a,k}^{EV}$	The arrival time for EV k [h].
$T_{d,k/n}^{EV/F}$	The departure time for EV k / ferry n [h].
$\lambda_t^{buy/sell}$	Price signals for purchasing/selling energy from/to the grid in period t [\$/kWh].
$u_{n,t}^{b-in}$	Binary parameter for the ferry n . 1 if ferry n is berthed-in mode, otherwise 0.
ΔT	Time granularity.
η_n	The efficiency for hydrogen use of fuel cell of ferry n .

D. VARIABLES

$m_{n,h,t}^{H,FC2F_{b-in}}$	The hydrogen amount used by the fuel cell of ferry n in berthed-in mode in period t [kg].
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$m_{h,t}^{H,Prod}$	The produced hydrogen amount by the electrolyzer and delivered to the port's storage unit in period t [kg].
$m_{n,h,t}^{H,P2F}$	The delivered hydrogen amount from port's storage unit to the ferry n in period t [kg].
$m_{h,t}^{H,P2F_{tot}}$	The total delivered hydrogen amount from the storage unit of port to the ferries' unit in period t [kg].
$m_{n,h,t}^{H,StoreF}$	The hydrogen amount in the hydrogen tank of ferry n in period t [kg].
$m_{h,t}^{H,StoreP}$	The stored hydrogen amount in the port's storage in period t [kg].
$P_{n,h,t}^{Char,F}$	Charging power of ferry n in period t [kW].
$P_{k,h,t}^{Char,EV}$	Charging power of EV k during the time interval when parked at the port [kW].
$P_{n,h,t}^{Dchar_{b-in}}$	Discharging power of ferry n in berthed-in mode in period t [kW].
$P_{h,t}^{ELC}$	Power of the electrolyzer in period t [kW].
$P_{n,h,t}^{FC2F_{b-in}}$	Power from fuel cell of the ferry n in berthed-in mode in period t [kW].
$P_{h,t}^{G2P}$	Power from grid to the port in period t [kW].
$P_{n,h,t}^{P2F}$	Power required by ferry n for battery charging and cold ironing in berthed-in mode in period t [kW].
$P_{h,t}^{P2EV_{tot}}$	Total charging power demand of EVs in period t [kW].
$P_{h,t}^{P2F_{tot}}$	Total battery charging and additional power demands of ferries during in the port in period t [kW].
$P_{h,t}^{P2G}$	Power injected to the grid from the port in period t [kW].
$SoE_{k,h,t}^{bat,EV}$	SoE of the EV k in period t [kWh].
$SoE_{n,h,t}^{bat,F}$	SoE of the ferry n in period t [kWh].
$u_{1,h,t}$	Binary variable for the grid interaction. 1 if G2P is available.
$u_{2,n,h,t}$	Binary variable for the battery. 1; if it is discharging.

I. INTRODUCTION

A. Motivation and Background

EVEN though transportation is essential for a variety of purposes, it has negative consequences in the form of a significant contribution to carbon emissions. Great efforts have been performing in many areas across to globe to reduce greenhouse gas (GHG) emissions [1]. According to International Energy Agency, 20% of the total emissions occur only in the transportation system, while the contribution of heat and electricity producers to this rate is approximately 40% in 2018 [2]. Governments have adopted strict policies to reduce GHG emissions globally and have encouraged

multi-stakeholders to adopt new emission reduction solutions [3]. Therefore, many studies have been carried out, and important steps have been taken to reduce emissions by integrating green vehicles and renewable energy sources into the transportation and power systems. Among the alternatives of green vehicular solutions, hydrogen fuel cell-based concepts bring important advantages as they have zero-emissions, as well as high efficiency, and similarity to conventionally fueled vehicles in behavior, power, and fueling time [4]. In the vein of integration of green vehicles and renewable energy sources, a vast number of studies have been conducted in almost all disciplines of the transportation sector. Maritime transportation is included a considerable amount of these studies. For example, the Zero Emission Fast Ferries project aims to develop a fuel cell/battery hybrid ferry in which battery and fuel cell will be utilized in shorter and longer journeys, respectively [5]. In addition to small ship systems, such as passenger ferries, there are also important projects aimed to reach zero emissions in large ship systems. Among them, The ShipFC project aims to design a ship with a 2 MW fuel cell capacity and to allow the ship to sail 3000 hours in a year with clean energy [6].

The integration of different types of transportation solutions, on the other hand, aims to reach several targets, such as improving public health and enhancing the quality of life in the community [7]. There are projects in many countries considering the penetration of various transport vehicles under the integrated transport concept [8]. The Sharenow project is conducted with the purpose of operating electric cars, airport, and public transport vehicles in a collaborative way [9].

It should be underlined that the option of continuing with green transportation for a trip that starts with green transportation offers sustainable energy transferring between vehicles and/or power system infrastructure of other green vehicles. Thus, it does not only provide an environmentally friendly system operation but also allows the existing power system to be used more efficiently. Besides the abovementioned opportunities, however, they create several uncertainties that should be studied, such as instability problems [10]. The arrival/departure times of green vehicles, as well as the power output of renewable sources, can be managed through the integration of several strategies.

B. Literature Summary

While there is a vast number of literature studies on the concept of electric vehicle (EV) parking lots, very few studies have investigated the integrated operation of EVs and other environmentally friendly transportation vehicles. Calvillo et al. [11] proposed a cost-minimization model within a linear programming framework for a system consisting of EVs, photovoltaic plant (PVP), and distributed energy resources incorporated into an electric metro station. However, uncertainties of EV and PVP as well as the collaboration of transportation vehicles were not included. Şengör et al. [12] proposed an EV parking lot management algorithm in the form of linear programming. Uncertainties of EVs were taken into consideration thanks to the real-time optimization method.

However, the implementation of renewable energy systems and coordination of green transportation vehicles were not modelled. Mathur et al. [13] modelled a parking lot management system for an optimal schedule of EV with the inclusion of PVP. On the other hand, the uncertainties caused by EVs and PVP power production, and power transactions to the grid were not considered in the proposed framework.

Besides utilizing clean vehicles in the transportation system, incorporating renewable-based power generation in the electrical system is of great importance which is the focus of a number of recent works. Among them, Oldenbroek et al. [14] designed a smart city where fuel cell EVs were used for transportation and all electricity demand was met by PVP and wind turbines. The surplus electricity was converted into hydrogen by electrolysis, and stored in the hydrogen tanks of fuel cell vehicles to supply the electricity in the event of a shortage in power generation. However, the grid and renewable energy exchange options were not considered. Farahani et al. [15] analyzed designing smart cities with similar topology by examining it from four different perspectives: technical, economic, operational and control, and institutional. The study used model predictive control to achieve optimal scheduling while minimizing operating costs and developed an agent-based model for institutional analysis. On the other hand, it did not account for the uncertainty of the arrival and departure times of fuel cell EVs.

When evaluating GHG emissions from maritime vessels during cruising, maneuvering, and while berthed at a port, [16] reveals that ships contribute the most pollution when they are berthed at the port. To address emissions from maritime vehicles, the concept of a green port has emerged as a significant solution. A green port integrates various measures, including the use of renewable energy resources to meet its energy needs, the replacement of diesel-based trucks with emission-free vehicles, and the implementation of advanced monitoring systems through digitalization. Moreover, the concept of cold ironing has emerged as a significant solution to mitigate ship emissions. It enables vessels to power down their main and auxiliary engines while meeting their energy requirements when docked, thanks to shore-side energy supply. These measures optimize operational planning and reduce emissions, as indicated in [17] and [18]. Although there are some studies in the literature on ports incorporating renewable energy sources and clean vehicles, studies are mainly focused on the energy management purposes of ports. Zhang et al. [19] described an energy management algorithm for an intelligent port in which power, heat, and gas energies were optimally scheduled to minimize the cost. However, the adoption of renewable energy sources was not considered in the presented scheme. Kanellou [20] proposed a decentralized control algorithm by using a multi-agent system method for managing the energy suppliers and consumers in the port. Inflexible and flexible loads, wind turbines as well as the power exchange with the grid were considered. Also, Molavi et al. [21] defined a two-stage stochastic mixed-integer model including four indices operational, environmental, safety, and security to enhance the positive impact of micro-grids on ports. The optimal installation status of distributed

energy systems was defined as the main problem and the operational planning of the port as a sub-problem, and the uncertainties associated with renewable energy power generation and power blackout were taken into account in the stochastic model. Although electric trucks and cranes were included in the port model, the EV parking lot and zero-emission ferry option were not modelled in [21]. Also, the integrated transportation system concept was not modelled in [20] and [21].

The primary distinction between this work and the authors' previous study [22] lies in enabling an integrated green transportation system, which includes a green port serving hydrogen-based green ferries and an adjacent EV parking lot. Moreover, the uncertainty related to EVs and PV is forecasted with the aid of Long Short-Term Memory (LSTM) method. In addition, it is worth underlining that the energy management strategy proposed in this current work is modeled using a receding horizon optimization approach to provide a more realistic plan that accounts for forecast errors.

Briefly, to summarize the previous literature examined in this paper, the studies presented in [11], [12], and [13] related to sole EV parking lot operation; [14] and [15] integrated to the fuel cell-based transportation solutions; [19], [20], [21], [22] did not consider green maritime solutions or the availability of EVs in port operations, nor did they explore the dual integration potential of different green transportation solutions in terms of transportation and power systems.

C. Contributions and the Paper Organization

This work propounds an innovative solution for sustainable transportation by introducing an energy management strategy for a green port equipped with a PVP. The port serves hybrid ferries with fuel cell/battery systems and includes a public EV parking lot. The proposed scheme promotes a dual integrated green transportation, enabling EV owners to seamlessly continue their green journey by using emission-free ferries. It carefully manages the EV charging schedule, ensuring that passengers return to vehicles with their batteries charged to the desired level. PVP and the grid are power suppliers of the port in which bi-directional power flow is considered between them. In addition to these power sources, the ferries' batteries can be charged by their fuel cells while they are berthed at the port. Furthermore, to mitigate ferry emissions, the green port offers a cold ironing facility that supplies power in addition to their fuel cell/battery sources to meet the energy requirements of berthed ferries, thereby eliminating the need for their combustion-based auxiliary engines. The contributions of the presented study are expressed threefold:

- 1) Mixed-integer linear programming (MILP) based real-time decision-making algorithm for bridging the gap between the real-world implementation of the proposed concept within the theoretical basis is presented.
- 2) The green transportation chain solution is achieved through the inclusion of an EV parking zone and zero-emission ferries within the framework of integrated transportation. This innovative solution allows one form of green transportation to support the energy needs of

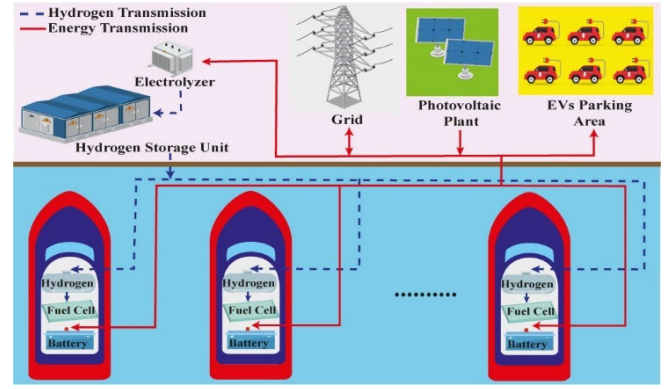


Fig. 1. The illustration of the proposed model including the flow of energy and hydrogen between parties.

another, creating a holistic and interconnected system. Furthermore, integrated transportation solutions enriched with PVP and hydrogen storage units along with the grid are evaluated for the first time in the literature.

- 3) The uncertainties related to the EVs and PVP production are captured by using LSTM forecasting method to obtain a more realistic approach.

The rest of the study is organized as follows: The mathematical background of the presented framework is described in Section II. Section III details the expected outcomes of the proposed management strategy. Section IV includes the concluding remarks and recommendations for further research.

II. METHODOLOGY

The illustration of the proposed real-time optimization-based model is demonstrated in Fig. 1. It is assumed that passengers arriving at the port with their EVs will have access to charging facilities to ensure their vehicles are charged to the desired level until they return. After that, they can continue their trip by zero-emission ferries available in the integrated transportation system. Moreover, the electricity required for the ferries and the EVs can be supplied by the PVP. Conversely, the electrolyzer generates hydrogen, which can be utilized by the ferries and stored in their storage units. Also, it is possible to ensure supply-demand balance with the transferred power from the upstream grid. It is important to clarify that the primary objective of the electricity generated through the PVP is to fulfill the electricity requirements at the port. This includes the production of hydrogen using electrolyzers, and the charging of EVs. Additionally, it serves the purpose of supplying power for recharging the batteries of the ferries, meeting their power requirements while they are berthed at the port. However, when there is either an excess or a shortage of electricity, a bidirectional energy exchange occurs between the grid and the port. The decision to initiate this energy exchange is determined by the proposed energy management algorithm, which considers various factors over different time frames to ensure the optimal utilization of the available resources.

A. Real-Time Optimization Method

The flow chart given in Fig. 2 illustrates the overall operation of the propounded scheme. First, the arrival and

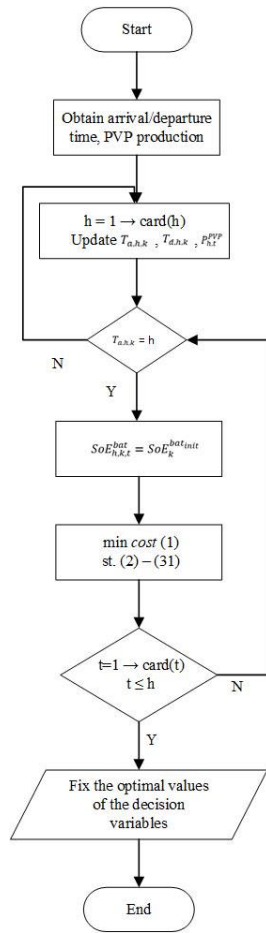


Fig. 2. The flowchart of the real-time optimization algorithm of the proposed model.

departure times of EVs are forecasted by using LSTM, a special type of recurrent neural network [23]. Also, PVP production at the beginning of the executed optimization round is predicted [24]. In this model, t represents the time intervals within an optimization horizon, and h indicates the executed optimization round. In each optimization round, the real-time values of the PVP power production and whether EVs arrived or not are checked for the t corresponding h . Subsequently, optimization is carried out with the objective of minimizing operational costs, considering both operational and infrastructural constraints. This optimization process utilizes the real-time values of photovoltaic generation and EVs' status to make immediate decisions. Importantly, the predictions for the subsequent optimization horizons are continually updated based on the most recent real-time data. This ensures that the proposed algorithm adapts dynamically to changing conditions and remains responsive to real-time variables.

After the optimization is carried out, the condition $t \leq h$ is checked for each optimization round. In case the condition is satisfied, the optimal values of the decision variables are fixed. The real-time values of the variables before the corresponding optimization interval are updated, and a new optimization is performed for each h value.

B. Mathematical Background of the Optimization Problem

In this subsection, the mathematical model of the port in a mixed-integer programming framework is presented aiming

to provide a cost-effective solution in terms of the daily operational cost of the port.

1) *Objective Function*: The objective function indicates the minimization of the cost which is given in (1).

$$\text{Minimize Cost} = \sum \left(P_{h,t}^{G2P} \cdot \lambda_t^{buy} \cdot \Delta T - P_{h,t}^{P2G} \cdot \lambda_t^{sell} \cdot \Delta T \right) \quad (1)$$

The payment and the profit of the port are calculated based on the power taken from the grid and the power supplied to the grid while considering the unit price, respectively. According to the differences between the payment and the gain of the port, the operational cost is obtained.

2) *Power Balance and Main Hydrogen Storage Unit Model*:

$$P_{h,t}^{G2P} + P_{h,t}^{PVP} = P_{h,t}^{ELC} + P_{h,t}^{P2EV_{tot}} + P_{h,t}^{P2F_{tot}} + P_{h,t}^{P2G}, \quad \forall h, t \quad (2)$$

$$P_{h,t}^{G2P} \leq N \cdot u_{1,h,t}, \quad \forall h, t \quad (3)$$

$$P_{h,t}^{P2G} \leq N \cdot (1 - u_{1,h,t}), \quad \forall h, t \quad (4)$$

$$P_{h,t}^{P2F_{tot}} = \sum_n P_{n,h,t}^{P2F}, \quad \forall n, h, t \quad (5)$$

$$P_{h,t}^{P2EV_{tot}} = \sum_k P_{k,h,t}^{Char,EV}, \quad \forall k, h, t \quad (6)$$

The demand of the port including electrolyzer, EVs, and ferries must be supplied by available power sources, namely, PVP and the grid. When PVP generates more power than the total demand, the excess energy can be sold to the grid. On the other hand, the remaining power should be injected by the upstream grid when the production is not adequate. The abovementioned circumstances are indicated by the constraint given in (2). Inequalities (3) and (4) are added to the model for preventing simultaneous buying and selling transactions. Each ferry requires power for charging its batteries, just like EVs, and to meet the operational demands during the berthed-in mode. Their power demand is obtained by (5) and (6), respectively. As given in (7), the required hydrogen for the fuel cell of the ferries is produced by the electrolyzer, which is determined by its consumption and the corresponding power-to-hydrogen amount constant. The electrolyzer has a power limit due to its physical constraints and this constraint is shown in (8).

$$m_{h,t}^{H,Prod} = P_{h,t}^{ELC} \cdot K_1 \cdot \Delta T, \quad \forall h, t \quad (7)$$

$$P_{h,t}^{ELC} \leq \lim^{P^{ELC}}, \quad \forall h, t \quad (8)$$

$$m_{h,t}^{H,StoreP} = m_{h,t}^{H,StoreP-init}, \quad \text{if } t = 1 \quad (9)$$

$$m_{h,t}^{H,StoreP} \geq m_{h,t}^{H,StoreP-min}, \quad \forall h, t \quad (10)$$

$$m_{h,t}^{H,StoreP} = m_{h,t-1}^{H,StoreP} + m_{h,t}^{H,Prod} - m_{h,t}^{H,P2F_{tot}}, \quad t > 1, \forall h, t \quad (11)$$

$$m_{h,t}^{H,P2F_{tot}} = \sum_n m_{n,h,t}^{H,P2F}, \quad \forall n, h, t \quad (12)$$

$$m_{h,t}^{H,StoreP} \leq m_{h,t}^{H,CapP}, \quad \forall h, t \quad (13)$$

The initial level of hydrogen in the port's storage unit is defined in (9) and it should have some amount of hydrogen

in case of any emergency situation as indicated in (10). The instantaneous hydrogen amount in the port's storage unit increases with the produced amount of hydrogen by the electrolyzer and decreases due to the total amount of transmitted hydrogen to ferries. This relationship is stated in (11). Moreover, the total transferred hydrogen amount from the storage unit of the port to ferries is given in (12). Also, the total hydrogen amount cannot exceed capacity of the hydrogen storage unit of the port as indicated in (13).

3) Fuel Cell/Battery Hybrid Ferry Model:

$$m_{n,h,t}^{H,StoreF} = m_{n,h,t}^{H,StoreF-init}, \quad \forall n, h, \text{ if } t = 1 \quad (14)$$

$$m_{n,h,t}^{H,StoreF} = m_{n,h,t-1}^{H,StoreF} + \left(m_{n,h,t}^{H,P2F} - m_{n,h,t}^{H,FC2Fb-in} \right) \times u_{n,t}^{b-in} - m_{n,t}^{H,FC2Fb-out} \left(1 - u_{n,t}^{b-in} \right), \quad \forall n, h, t \text{ if } t > 1 \quad (15)$$

$$m_{n,h,t}^{H,P2F} \leq \lim^{H,P2F}, \quad \forall n, h, t \quad (16)$$

$$m_{n,h,t}^{H,FC2Fb-in} = \frac{K_{2,n}}{\eta_n} \cdot \Delta T \cdot P_{n,h,t}^{FC2Fb-in}, \quad \forall n, h, t \quad (17)$$

$$m_{n,t}^{H,FC2Fb-out} = \frac{K_{2,n}}{\eta_n} \cdot \Delta T \cdot P_{n,t}^{FC2Fb-out}, \quad \forall n, h, t \quad (18)$$

$$m_{n,h,t}^{H,StoreF} \leq m_{n,h,t}^{H,CapF}, \quad \forall n, h, t \quad (19)$$

The hydrogen amount in the hydrogen tank of each ferry at the initial time is given in (14). Equation (15) indicates the variation of hydrogen level in each ferries' tank unit. Herein, $u_{n,h,t}^{b-in}$ reflects the location of the relevant ferry during each time period. While a ferry is at the port, the hydrogen level increases as hydrogen is transferred from the port to the ferry's storage unit and decreases as the fuel cell consumes hydrogen. On the other hand, its level reduces due to the consumed amount of hydrogen during the sailing time of the ferry. The amount of hydrogen which is coming from the storage unit of the port during a time period has a limit and it is shown in (16). The consumed hydrogen amount in berthed-in and berthed-out modes is related to power consumption and power-to-hydrogen amount constant as given in (17) and (18), respectively.

$$SoE_{n,h,t}^{bat,F} = SoE_{n,t}^{batmin,F}, \quad \forall n, h, \text{ if } t = 1 \quad (20)$$

$$SoE_{n,h,t}^{bat,F} = SoE_{n,h,t-1}^{bat,F} + \left(P_{n,h,t}^{Char,F} \cdot CE \cdot \Delta T - \frac{P_{n,t}^{Dcharb-in} \cdot \Delta T}{DE} \right) \times u_{n,t}^{b-in} - \left(\frac{P_{n,t}^{Dcharb-out} \cdot \Delta T}{DE} \left(1 - u_{n,t}^{b-in} \right) \right), \quad \forall n, h, t > 1 \quad (21)$$

$$P_{n,t}^{Dcharb-out} = K_{3,n} \cdot P_{n,t}^{Sail}, \quad \forall n, t \quad (22)$$

$$P_{n,t}^{FC2Fb-out} = (1 - K_{3,n}) \cdot P_{n,t}^{Sail}, \quad \forall n, t \quad (23)$$

$$SoE_{n,t}^{batmin,F} \leq SoE_{n,h,t}^{bat,F} \leq SoE_{n,t}^{batcap,F}, \quad \forall n, h, t \quad (24)$$

$$P_{n,h,t}^{FC2Fb-in} + P_{n,h,t}^{Dcharb-in} + P_{n,h,t}^{P2F} = P_{n,h,t}^{Char,F} + P_{n,h,t}^{Serv}, \quad \forall n, h, t, \text{ if } u_{n,t}^{b-in} = 1 \quad (25)$$

$$P_{n,h,t}^{Char,F} \leq CR_n^F \cdot (1 - u_{2,n,t}), \quad \forall n, h, t \quad (26)$$

$$P_{n,h,t}^{Dcharb-in} \leq DR_n^F \cdot u_{2,n,t}, \quad \forall n, h, t \quad (27)$$

As it is defined in (19) the hydrogen storage unit of each ferry cannot keep hydrogen more than its capacity. It is assumed that the energy level of the ferries' batteries has an initial value at the beginning of the simulation as described in (20). Equation (21) defines the state-of-energy (SoE) of the ferries' batteries for the rest of the day. The battery is expected to supply a fraction of the total power needed by each ferry while it is berthed-out, with the fuel cell supplying the remainder as indicated in (22) and (23), respectively. The energy level of batteries cannot be less than their minimum level and cannot be more than their capacity as given in (24). Equation (25) indicates that the power required for charging the ferries' battery and supporting their operations at the port can be provided by the port or their own fuel cell or battery. To prevent charging and discharging modes of operation at the same time, inequalities (26) and (27) are added to the model. These equations also define the upper bound of the charging and discharging power rate of the batteries of the ferries.

4) Electric Vehicle Model:

$$SoE_{k,h,t}^{bat,EV} = SoE_k^{batinit,EV}, \quad \forall k, h, \text{ if } t = T_{a,k} \quad (28)$$

$$SoE_{k,h,t}^{bat,EV} = SoE_{k,h,t-1}^{bat,EV} + \left(P_{k,h,t}^{Char,EV} \cdot CE \cdot \Delta T \right), \quad \forall k, h, \text{ if } T_{a,k} < t < T_{d,k} \quad (29)$$

$$SoE_{k,h,t}^{bat,EV} \geq SoE_k^{batdes,EV}, \quad \forall k, h, \text{ if } t = T_{d,k} \quad (30)$$

$$SoE_k^{batmin,EV} \leq SoE_{k,h,t}^{bat,EV} \leq SoE_k^{batcap,EV}, \quad \forall k, h, t \quad (31)$$

The energy level of the batteries of the EVs is considered to have an initial value at the arrival time, as shown in (28). Equation (29) indicates that while EVs are parked at the port, they can be charged and the SoE level of their batteries ascends regarding to charging power value. As integrated by (30) and (31), EVs should have reached their desired SoE at the time of their departure and it should not fall below its minimum value or exceed its capacity.

III. TEST AND RESULT

The stochastic-based energy management algorithm aims to minimize the cost of energy transactions between the upstream grid and the port. The propounded scheme is modeled in General Algebraic Modeling System (GAMS) v.24.1.3 by using CPLEX v.12 solver [25]. The time granularity is assumed as 15 min in all numerical analyses for a 24h simulation horizon. Note that, the execution of the optimal decision-making algorithm for the all horizons on a computer with 2.3 GHz CPU and 32 GB RAM takes approximately one minute and thirty seconds.

A. Input Data

The Istanbul Sea Buses (IDO) Harbor in Bursa [26] is modified according to the possibilities of the mentioned port in this study. The hybrid ferries are modeled considering the data obtained from the IDO Harbor ferry fleet with a main 1500 kW internal combustion engine. After the first ferry completes its initial voyage, its time duration in the port for battery charging and hydrogen intake is 15 minutes. However, considering the battery's storage capacity and charging power rate, it can

TABLE I
ARRIVAL AND DEPARTURE TIME OF THE FERRIES

Ferry 1	Departure Time	04:15	07:15	11:45	15:45	-
	Arrival Time	-	07:00	11:00	15:00	19:00
Ferry 2	Departure Time	05:45	09:45	13:45	17:45	-
	Arrival Time	-	09:00	13:00	17:00	20:30

only provide a maximum of 10% of its total energy demand. Therefore, it is assumed that the primary energy source for the ferries is the fuel cell, with 90% of their total energy demand being supplied by the fuel cell, while the remaining 10% is covered by the battery. According to the aforementioned assumptions, the battery and hydrogen capacities of the ferries are defined to be 450 kWh and 182 kg, respectively. The arrival and departure times of the hybrid ferries are determined by the timetable of the IDO Yenikapi Harbor's ferries and shown in Table I [27]. Furthermore, the fuel cell system's efficiency is determined as 50% [28].

The transformer unit of the port has a 3200 kW power capacity. Based on the hydrogen demand of the port, an appropriate electrolyzer is chosen from the market. The chosen electrolyzer has a maximum power requirement of 2280 kW. In addition, it is assumed that the port's main storage facility will have a minimum 200 kg of hydrogen available to be able to fill the hydrogen tanks of two ferries in the event of an emergency. LSTM, a special type of recurrent neural network, is used to predict the real-time values of the arrival/departure times, and parking duration of 273 EVs. In this study, a 4-year dataset from Istanbul's parking lots, comprising 1380 days and 132480 data points at 15-minute intervals is utilized. This dataset is split into 80% training data and 20% test data. By considering in each 280 data (3 days), the 281st data is estimated. The LSTM configuration used in this research is summarized in the Table II. The mean squared error metric was used to determine whether a prediction was successful after 105 seconds of training, reaching 1,696 errors in the training data and 1,809 errors in the test data. The proposed LSTM algorithm exhibits high efficiency, continuously updating its forecasts during training by assessing the differences between its forecasts and the actual values. For a more comprehensive examination of its efficiency and accuracy, a prior study authored by some of the contributors to this paper, which offers an in-depth analysis of the algorithm's performance, is recommended to be referred to [23]. Also, the expected and real time values of the energy production of PVP are taken as a [29]. On the other hand, Fig. 3 illustrates the variation of electricity price signal with respect to time for energy transactions between the port and the upstream grid [30].

B. Simulation Results

The simulation starts at 00:00 at the beginning of the day and the results are obtained according to the expected PVP production, as well as arrival/departure times, and parking duration of EVs. From the beginning of the simulation, the model is carried out by considering the actual PVP and EV

TABLE II
LSTM CONFIGURATION SPECIFICATIONS

Data length	132 480
Day	1380
Frequency	15 min
Train/Test size	105695/26207
Step size	288
Input shape	(1,288)
Activation function	ReLU
Model	LSTM(300) / Dense(1)
Optimizer	Adam
Loss type	Mean Squared Error
Final epoch	15
Training time	105 second
Train RMSE	1.696
Test RMSE	1.809

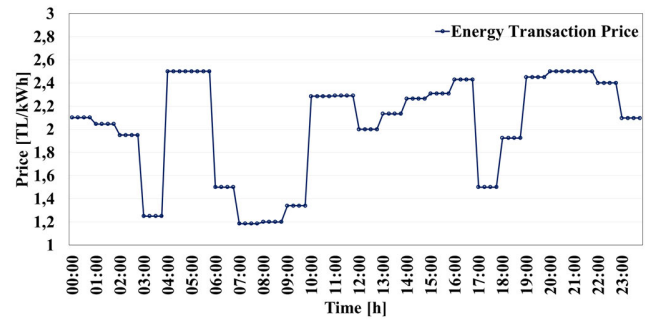


Fig. 3. The electricity price for bi-directional energy transactions [26].

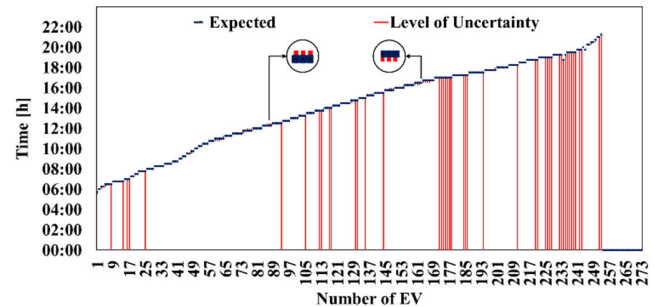


Fig. 4. Expected arrival time of EVs and the level of uncertainty of the arrival time of EVs.

values before each time point. Then, the expected PVP and EV values for the next periods in each time slot are obtained. The results are discussed in detail for four different hours i.e., 00:00, 08:00, 16:00, and 23:45. In order to emphasize the efficacy of the proposed algorithm and test it under different circumstances, 12 cases are created and analyzed in detail.

Figure 4 illustrates the expected and actual values related to being in the parking area for EVs, including arrival/departure and parking times. In the case studies of interest, the EVs that were expected to arrive, did not arrive, or did not arrive despite being expected were taken into account. Expected arrival times of the EVs are shown by the expected line. Red bars represent the level of the uncertainty by showing the differences between the actual and expected arrival time of the EVs. The situation where the red bars are above the expected line means that related EV arrived at the port later than expected. The span of the red bar defines how much time difference, and similarly, the case where the red bars are

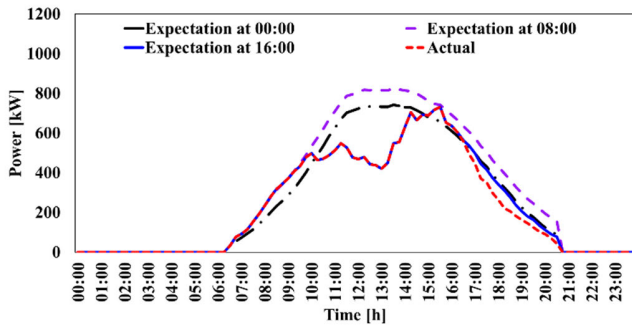


Fig. 5. Power generation of the PVP in different executions.

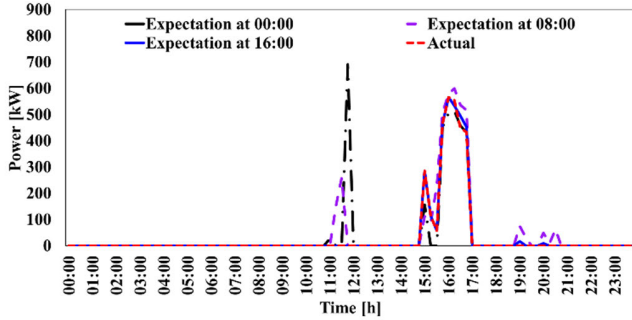


Fig. 6. Injected power into the upstream grid by the port in different executions.

below the expected line indicates how much sooner the related EV arrived than expected. The red bars extending from the expected time to the start time indicate that the relevant EVs have not arrived. To clearly explain the figure, the expected and actual arrival times of the EVs are shown by zooming into the cases in which the EVs arrived later and sooner than expected, respectively. In detail, almost 7% of the 273 EVs arrived earlier than expected, and approximately 5.5% arrived later than expected. Besides, nearly 16% did not come while they are expected, and about 7% came unexpectedly. Figure 5 shows the actual and expected power generation of the PVP at 00:00, 08:00, and 16:00 executions. In different executions, power generation is estimated for the next hours based on the real-time data up to the hour of the expectation. When the day-ahead expectation is compared with the actual power generation, it is seen that there are significant differences between them.

Expected and actual power transactions from port to grid (P2G) and grid to port (G2P) are shown in Fig. 6 and Fig. 7, respectively. It can be seen that the power transactions are strongly affected by the difference between the expected and actual values of the PVP power production and presence of EVs. When analyzing the expectation line at 00.00, the power transaction P2G is expected at 11.00. However, due to the power production of the solar panel being less than expected at that time, the resulting power transaction G2P is shown in the actual line.

The total demand of the port, consisting of the electrolyzer power, ferries' demand supplied directly by the port, and EV charging are shown in Fig. 8. It is to be noted that the electrolyzer covers a large portion of the port's power demand to meet the hydrogen needs of the ferries, with the fuel cell

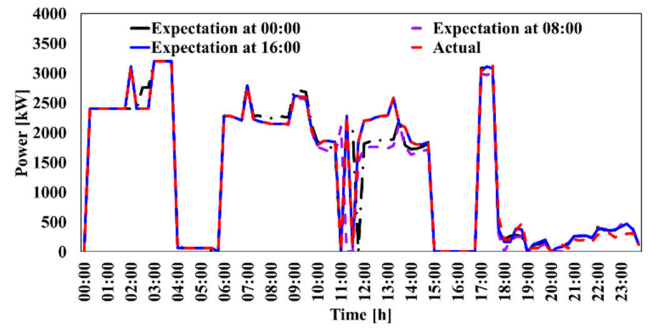


Fig. 7. Power drawn from the upstream grid by the port in different executions.

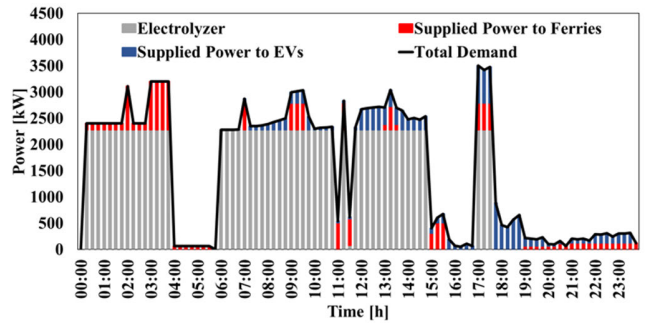


Fig. 8. The total demand of the port (with the electrolyzer, ferries and EVs).

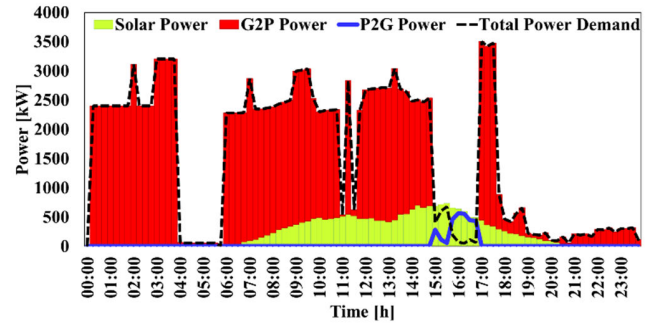


Fig. 9. The power transaction between the upstream grid, the port and PVP.

units serving as the primary energy source. The total power demand of the port is supplied by the PVP or the upstream grid as illustrated in Fig. 9. It can be observed that between 15:00 and 17:00 when the power production of the PVP is higher than the demand of the port, then the power transaction P2G is obtained. Figure 10 represents the total hydrogen amount in the port's storage unit at different execution time. The lower limit for the hydrogen amount in the port's storage unit is established at 200 kg in accordance with the aforementioned assumption.

Moreover, the electrolyzer produces hydrogen in accordance with the ferries' demand and the cost of energy transactions. Therefore, the hydrogen level of the storage unit of the port is always higher than 200 kg. According to the actual and expected the PVP power production at 00:00, 08:00 and 16:00 and electricity price, different level of hydrogen is produced by the electrolyzer and stored in the unit. Also, the ferry that came to the port to meet the needs for its last voyage arrived

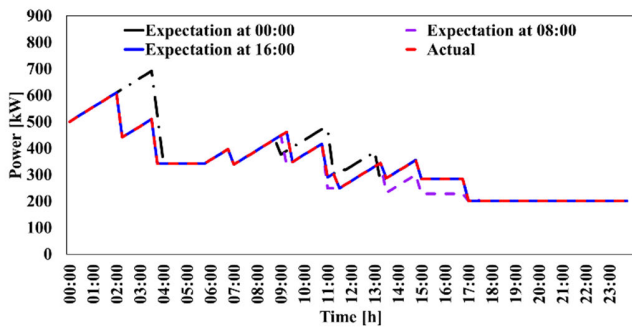


Fig. 10. The hydrogen amount in the port storage in different executions.

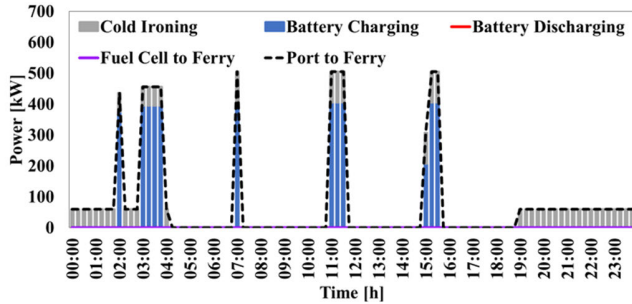


Fig. 11. Analytics of power transaction for the Ferry 1.

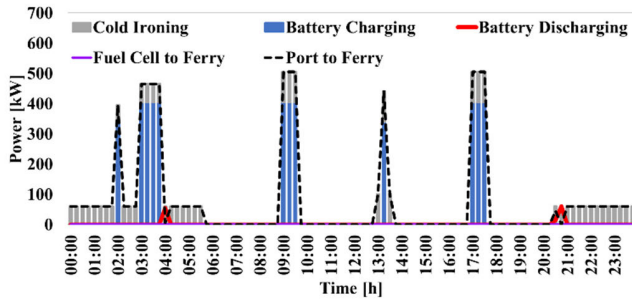


Fig. 12. Analytics of power transaction for the Ferry 2.

at 17.00. For this reason, there has been no change in the hydrogen amount of the port's storage unit since 17.00.

Figures 11 and 12 depict the analytics of the power transaction in the berthed-in mode for Ferry 1 and Ferry 2, respectively. While the ferries are in the port, they have power demand for their battery charging and cold ironing. The power demand of ferries can be supplied by the port or their batteries and fuel cells.

It can be observed that the power flow from the port is preferred as a supplier for Ferry 1 over the fuel cell and battery due to the efficiency. However, for the time intervals 04:00-04:15 and 20:30-21:00, power demand of the Ferry 2 is supplied by its own battery. Before departing from the port, its battery is charged up to 450 kWh, which represents the upper limit of its battery capacity. Since the energy transaction price is at its lowest and the battery is fully charged to its maximum capacity, the excess energy is used to meet the power demand within the port. Also, it has more energy than the lower limit of its battery when it completes the last navigation and turns back to the port. Because of the high energy transaction price,

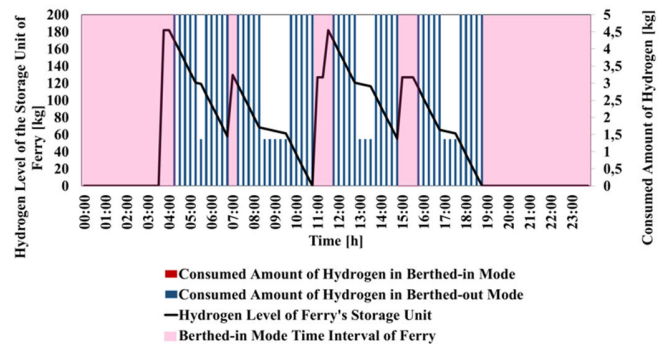


Fig. 13. The consumed hydrogen amount variation of Ferry 1.

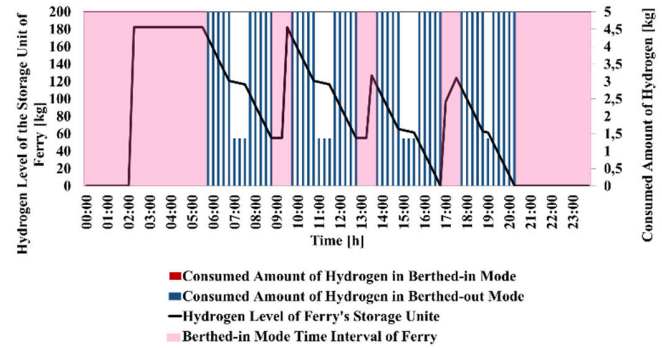


Fig. 14. The consumed hydrogen amount variation of Ferry 2.

it provides an excess of energy to the ferry between 20:30 and 21:00.

Figures 13 and 14 show the variation of the hydrogen amount in the hydrogen tank of Ferry 1 and Ferry 2, respectively. The hydrogen level in the storage tank of the ferries decreases when they are in berthed-out mode and the required hydrogen amount is transferred to the tank while they are berthed at the port as the pink areas show. Due to its low efficiency, the fuel cell is not utilized as a power source to fulfill the power demand of the ferries while they are in the berthed-in mode. Therefore, there was no hydrogen consumption during the berthed-in mode of the ferries. While the SoE variation of Ferry 1 is shown in Fig. 15, this is illustrated in Fig. 16 for Ferry 2. When the ferries are sailing, batteries are discharged to fulfill a certain part of the power demand and they are charged while they are berthed at the port. As shown in the power analytics of the Ferry 2, battery discharging during the time intervals 04:00-04:15 and 20:30-21:00 is seen.

To highlight the impact of the real-time application and the effectiveness of the proposed algorithm, thirteen different cases are created. Among these cases, the optimization algorithm is executed regarding the day-ahead expectations in Base Case and the proposed real-time algorithm is executed with the actual PVP production and EVs arrival/departure times in all other cases. The grid transaction limit (GTL) is determined to be 75% and 50% of the maximum power rating of the transformer. As can be seen in Fig. 9, peak power flow from G2P occurs at 02:00-04:00 and 17:00-19:00 when the transaction energy price is lowest and duration of GTL is defined according to those time intervals. Results are analyzed

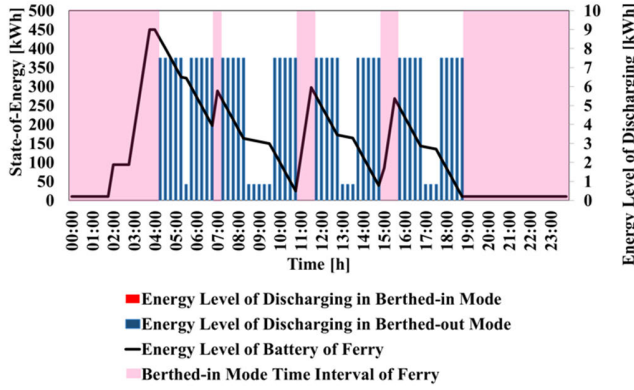


Fig. 15. SoE variation of Ferry 1.

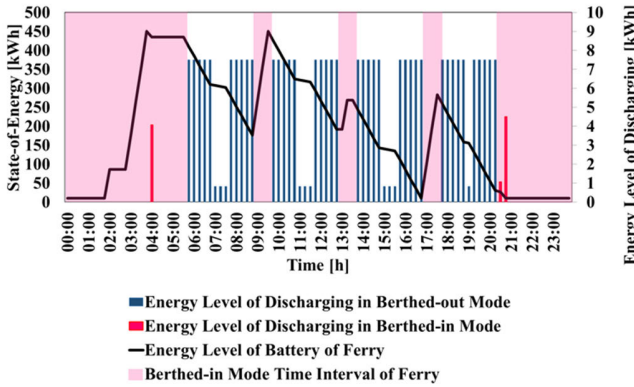


Fig. 16. SoE variation for Ferry 2.

regarding the operational cost and load factor of the port as shown in Table III.

In the Reference Case, the proposed algorithm leverages real-time data, including actual PVP production and EV arrival/departure times, without any constraints on the power flow from G2P. In contrast, the Base Case employs non-real-time optimization based on day-ahead expectations for EV arrival/departure times and PVP production. When comparing these day-ahead expectations to the actual values for EVs and PVP, a notable difference is observed. Specifically, there was a 2.022% variance in cost and a 5.151% variance in the load factor. The cases between Case1 and Case 4 limit the peak power in the morning hours.

When the GTL value decreases and duration of the limit increases, the cost and load factor grow substantially. Peak power limitations are enforced during the evening hours in cases from Case 5 to Case 8. As the energy transaction price is typically low during these evening hours, an extension of the GTL period leads to an increase in cost. Conversely, as the final voyage concludes at 17:45, and the ferries do not operate until 04:15 the next day, the GTL imposed during the evening hours do not significantly affect the load factor because more cost-effective energy transactions become available the following morning. Peak power limit in the morning and evening hours are restricted in the cases from Case 9 to Case 12. In addition to obtaining yielding results similar to those in previous cases, it can be seen from Case 11 and Case 12 that the enhancements in the load factor are the most significant

TABLE III
OPERATIONAL COST OF THE PORT AND LOAD FACTOR UNDER DIFFERENT GTL AND LIMIT DURATION CIRCUMSTANCES

Case Study	GTL [kW]	Duration	Cost [TL]	Load Factor	Increase Rate in Load Factor
Reference Case	-	-	54688.64	0.419	-
Base Case	-	-	53583.07	0.397	-5.151%
Case 1	2400	02:00-04:00	55349.73	0.419	0.009%
Case 2	2400	00:00-04:00	55548.39	0.430	2.708%
Case 3	1600	02:00-04:00	56463.67	0.418	-0.305%
Case 4	1600	00:00-04:00	57056.49	0.425	1.331%
Case 5	2400	17:00-19:00	54974.31	0.420	-0.001%
Case 6	2400	17:00-00:00	54974.31	0.419	-0.001%
Case 7	1600	17:00-19:00	55446.58	0.419	-0.001%
Case 8	1600	17:00-00:00	55446.58	0.419	-0.001%
Case 9	2400	02:00-04:00 and 17:00-19:00	55635.39	0.418	-0.01%
Case 10	2400	00:00-04:00 and 17:00-00:00	55857.83	0.482	-0.482%
Case 11	1600	02:00-04:00 and 17:00-19:00	57230.39	0.417	15.145%
Case 12	1600	00:00-04:00 and 17:00-00:00	57932.60	0.475	13.294%

among all cases. This can be explained by the strict limitations on grid transactions and the extended duration of the limit. In line with the case comparisons, a stricter grid limit and a longer duration time of the limit provide an improvement in the load factor.

Thus, the operating capacity of the transformer is not placed under strain, prolonging its service life, and avoiding the need for a transformer with higher power due to the absence of instantaneous high-power demands. Despite the mentioned benefits for the operator and the end-user, the restriction on the grid power causes the energy demand to be met in a more expensive time, resulting from an increase in the operating cost. while also accounting for uncertainties in PVP production and EV parameters.

IV. CONCLUSION

In this study, a green port serving hybrid ferries consisting of fuel cell/battery including a parking area for EVs was modeled. A real-time energy management algorithm was introduced with the aim of minimizing operational costs, taking into consideration energy transactions between the port and the grid. Importantly, this study represents the first instance in the literature where an energy management strategy was devised for a port hosting a public EV parking lot, PVP, hydrogen storage units, and grid interaction using a real-time rolling horizon approach. Furthermore, the integration of two different green transportation options was one of the significant contributions made by the study. According to the results obtained throughout the work, the amount of GTL and the duration of its application can negatively impact port operations unless an effective energy consumption management strategy is implemented. Thanks to the proposed algorithm, the scheduling of GTL time and its amount can be determined in an effective manner. As an extended version of the study, the internal energy management model together with the battery

degradation of ferries for ferries could be included. It is essential to recognize the limitations of this study. While the concept of a green transportation chain significantly enhances the overall effectiveness of our environmentally friendly transportation system, it is important to acknowledge and address the challenges associated with its implementation. In future studies, we will focus on addressing the specific challenges that may arise, particularly contingency issues within the green transportation chain. Furthermore, with regard to hydrogen supply, this study exclusively relies upon electrolyzers at the port for hydrogen production, with a certain level of hydrogen stored to ensure reliability. To improve this aspect, an investigation into the feasibility of a hydrogen pipeline connection is warranted. Additionally, the potential value of including battery-based energy storage systems to increase the port's energy flexibility and transaction capabilities is acknowledged. These enhancements would contribute to the establishment of a more comprehensive and adaptable energy management system for the port.

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