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A MATHEMATICAL MODEL FOR ELECTRICITY DEMAND OPTIMIZATION WITH ENERGY STORAGE SYSTEM INTEGRATION FOR A SEAPORT

МАТЕМАТИЧНА МОДЕЛЬ ОПТИМІЗАЦІЇ ПОПИТУ НА ЕЛЕКТРОЕНЕРГІЮ З ІНТЕГРАЦІЄЮ СИСТЕМ НАКОПИЧЕННЯ ЕНЕРГІЇ ДЛЯ МОРСЬКОГО ПОРТУ

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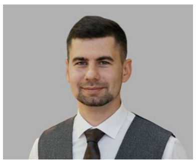

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Abstract. In this article, a mathematical model for electricity demand optimization in a seaport, integrating Energy Storage Systems (ESS), was developed and verified. The model aims to minimize operational costs and enhance energy resilience. The research is based on developing a mathematical model formulated as a linear programming problem to minimize total operational electricity costs over a specified planning horizon. It accounts for the optimization of electricity purchasing profiles from the grid, the use of self-generated renewable energy sources (RES), and ESS charging and discharging modes.

Key input parameters were defined, including forecasted loads, RES generation, dynamic tariffs, grid limits, and ESS characteristics. The objective function minimizes the sum of electricity purchase costs, ESS degradation costs, and penalties. The system of constraints includes power balance, ESS charge dynamics, limits on exceeding grid power limits, and variable ranges.

The model was implemented and verified using simulations in MATLAB. The simulation results demonstrated that the integration of ESS and RES significantly reduces peak loads and optimizes electricity purchases from the grid. RES generation is effectively utilized to cover the loads. The ESS charging/discharging strategy shows effective energy arbitrage. The dynamics of the ESS charge confirm that the battery charge level remains within permissible limits.

A comparison of baseline and optimized power purchases visually demonstrates significant smoothing of the consumption profile and peak reduction, directly indicating economic savings. For the first time, a comprehensive mathematical model for demand optimization in a seaport has been developed, simultaneously considering dynamic tariffs, the integration of intermittent RES, optimal ESS management, and specific operational features of the port.

The model provides ports with a tool for the significant reduction of electricity operational costs, increased energy resilience, and self-sufficiency. Investments in ESS and intelligent control systems are strategically justified for enhancing competitiveness and complying with modern environmental standards.

Key words: mathematical model; demand optimization; electricity; energy Storage Systems; renewable energy sources; linear programming; peak load; energy arbitrage; energy resilience.

Анотація. У статті було розроблено та проведено верифікацію математичної моделі оптимізації попиту на електроенергію для морського порту з інтеграцією системи накопичення енергії (СНЕ), спрямованої на мінімізацію операційних витрат і підвищення енергетичної стійкості. Дослідження ґрунтується на розробці математичної моделі, сформульованої як задача лінійного програмування для мінімізації сумарних операційних витрат на електроенергію протягом заданого горизонту планування. Вона враховує оптимізацію профілів купівлі електроенергії з мережі, використання власної генерації відновлювальних джерел енергії (ВДЕ), а також режимів зарядки та розрядки СНЕ. Визначено ключові вхідні параметри (прогнозоване навантаження, генерація ВДЕ, динамічні тарифи, ліміти мережі, характеристики СНЕ). Цільова функція мінімізує суму витрат на купівлю, деградацію СНЕ та штрафи. Система обмежень передбачає баланс потужностей, динаміку заряду СНЕ, обмеження на перевищення ліміту мережі та діапазони змінних. Модель реалізовано та верифіковано за допомогою імітаційного моделювання в MATLAB. Результати моделювання показали, що інтеграція СНЕ та ВДЕ значно знижує пікові навантаження й оптимізує купівлю електроенергії з мережі. Генерація ВДЕ ефективно використовується для покриття навантаження. Стратегія зарядки / розрядки СНЕ демонструє ефективний енергетичний арбітраж. Динаміка заряду СНЕ підтверджує, що рівень заряду батареї залишається в допустимих межах. Порівняння базової та оптимізованої купівлі потужності візуально демонструє значне згладжування профілю споживання та зниження піків, що прямо вказує на економічну економію. Уперше розроблено комплексну математичну модель оптимізації попиту для морського порту, яка одночасно враховує динамічні тарифи, інтеграцію нестабільних ВДЕ, оптимальне управління СНЕ та специфічні операційні особливості порту. Модель надає портам інструмент для значного зниження операційних витрат на електроенергію, підвищення енергетичної стійкості та здатності до самозабезпечення. Інвестиції в СНЕ та інтелектуальні системи управління є стратегічно виправданими для підвищення конкурентоспроможності та відповідності екологічним стандартам.

Ключові слова: математична модель; оптимізація попиту; електроенергія; системи накопичення енергії; відновлювані джерела енергії; лінійне програмування; пікове навантаження; енергетичний арбітраж; енергетична стійкість.

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Introduction. Sea ports, as key transport and logistics hubs, are characterized by significant and variable electricity consumption. Peak loads, caused by the simultaneous operation of port equipment (cranes, conveyors, lighting, dock locks, charging stations for vessels and electrical equipment), pose substantial challenges to grid stability and lead to significant economic costs. These costs are due to both high tariffs for peak power and potential penalties for exceeding contractual consumption limits. Furthermore, traditional reliance on the centralized grid makes ports vulnerable to electricity supply interruptions, which can result in cargo handling delays and financial losses [1, 2, 3].

Growing attention to environmental sustainability and decarbonization also encourages ports to integrate renewable energy sources (RES), such as solar panels or small wind turbines. However, the variability of RES generation creates additional problems for balancing electricity supply and demand. The use of energy storage systems (ESS), particularly battery energy storage, is considered a promising solution for smoothing peak loads, increasing energy independence, and effectively integrating RES. Nevertheless, optimal management of ESS under variable loads and tariffs, as well as integration with various electricity sources, requires the development of a complex mathematical optimization model that would account for all these factors [4, 5].

Analysis of Research and Publications. The issue of optimizing energy consumption in industrial consumers and integrating ESS is actively explored in the global scientific literature. A significant number of publications focus on optimizing electricity consumption. Studies such as [6] and [7] consider demand management models for industrial consumers with the aim of reducing peak loads. They often use linear programming methods to minimize costs.

Research on the integration of RES [8, 9] analyzes the challenges and opportunities of integrating solar and wind generation into microgrids, as well as the role of ESS in smoothing power fluctuations from RES.

Numerous studies are dedicated to the role of ESS in reducing electricity costs through arbitrage (purchasing energy at low prices, selling or using at high prices) and peak shaving. Among them, studies [10, 11] propose mathematical approaches to optimizing battery operation [12].

Research [13, 14, 15] examines the energy systems of sea and river ports. However, most of them focus on vessel electrification or emission reduction, rather than comprehensive demand management and ESS integration, taking into account the specifics of seaports (e.g., equipment operation schedules, different scales compared to industrial ports).

Despite the significant volume of research in each of these areas, there is a gap in comprehensive mathematical models that would simultaneously optimize demand, account for dynamic tariffs, integrate variable RES, and manage ESS operation, considering the specific operational features of a seaport. Existing models are often simplified or do not account for all interdependencies between these components.

The goal of this research is to develop and verify a mathematical model for electricity demand optimization in a seaport with the integration of energy storage systems, aimed at minimizing operational electricity costs and enhancing energy resilience. To achieve this goal, the following tasks were set:

1. Identify key parameters and constraints influencing electricity consumption in a seaport (equipment operation schedules, dynamic tariffs, RES and ESS characteristics).
2. Formulate an optimization objective function that minimizes total electricity costs, including the cost of purchasing from the grid, the cost of using RES, and ESS degradation.
3. Develop a system of constraints that reflects the physical and operational characteristics of the port's power grid, RES, and ESS (e.g., ESS charging/discharging power, ESS capacity, grid power limits).
4. Integrate RES generation forecasts and load forecasts into the model to ensure adaptive control.
5. Verify the developed model through simulation using real or typical seaport data, demonstrating its economic feasibility.

Main Material. Energy efficiency and sustainability are priority tasks for modern industrial facilities, especially for sea ports, which are characterized by significant and dynamic electricity consumption. The integration of ESS and RES allows for increased flexibility of the energy system, reduced dependence on the centralized grid, and optimized operational costs. Effective management of these components requires the development of comprehensive mathematical models.

Let's consider a detailed description of a mathematical model for optimizing the energy consumption of a sea port, which accounts for the integration of ESS and RES. The key parameters of the model, its objective function, and the system of constraints are discussed. The implementation of the model in the MATLAB environment using linear programming tools for minimizing operational costs and improving energy efficiency is demonstrated.

The problem is formulated as a Linear Programming (LP) problem, aiming to minimize the total operational electricity costs for a sea port over a specified planning horizon. The optimization includes determining optimal profiles for electricity purchases from the grid, utilizing self-generated RES, and ESS charging and discharging modes.

The model operates with a set of input parameters and variables that characterize the port's energy system and its interaction with the external environment. In the MATLAB environment, these parameters are defined at the beginning of the script, and the variables are the result of the optimization solver's operation.

Parameters are defined as scalar values or time-indexed vectors:

$$t \in \{1, ..., T\},$$

where T is the number of time intervals in the planning horizon (e.g., 24 hours).

The input parameters are the foundation of the model, reflecting the basic characteristics of the port's energy consumption and external conditions. They are known quantities supplied as input to the optimization problem. Input data for the load profile and generation are specified as vectors of known variables. The forecasted electrical load of the river port at time t is represented by a vector of known data P_{load}, in kW. This data is typically obtained from historical consumption records, weather forecasts (to account for heating/cooling), and port operational schedules (vessel arrivals/departures, crane operations, warehouse operations). The accuracy of this profile is critical for adequate modeling.

Forecasted electricity generation from RES at time t – P_{RES}, kW, is also a vector of known data (e.g., solar panels, wind turbines). This data is based on meteorological forecasts (solar insolation, wind speed) and the characteristics of the installed RES.

Grid tariffs include the cost of purchasing electricity from the centralized grid at time t – C_{grid}, UAH/kWh (accounting for dynamic tariffs). Tariffs can vary by hour of the day (night, day, peak), day of the week, season, or reflect real market prices (spot prices) if the port participates in the relevant market segment. Accounting for these changes is key to the energy arbitrage strategy.

The contractual limit of the maximum power that can be consumed from the grid – $P_{grid,\max}$, kW. Exceeding this limit can lead to significant penalties or disconnections. This limitation encourages the port to flatten consumption.

For grid limitations, penalties for exceeding the contractual power limit were considered – $C_{penalty}$, UAH/kW. This parameter is crucial in the objective function and prompts the model to avoid peak loads that exceed the established limit. For monthly accounting of peak power, this penalty can be adapted to reflect a monthly fee.

ESS parameters define the technical characteristics of the battery and influence its functioning and longevity. They include the maximum battery capacity – $E_{batt,\max}$, kWh, the maximum charging power $P_{charge,\max}$ of the ESS, kW, the efficiency of the battery discharge/charge process of the ESS – η, the cost of ESS degradation per unit of energy throughput (depreciation) – C_{deg}, UAH/kWh, and the initial state of charge of the battery at the beginning of the optimization horizon – SoC_0, kWh.

Also, when formulating the mathematical model, optimization variables must be considered – these are unknown quantities that the model calculates to achieve the objective function while adhering to all constraints.

The optimized power profile purchased from the centralized grid at each time interval t – $P_{grid,opt}$, kW. This is a key result showing how the port should interact with the grid.

The optimized power directed to charging the ESS at time t – $P_{charge,opt}$, kW. It shows when and with what intensity the battery should be charged.

The optimized power discharged by the ESS and supplied to the port consumers at time t – $P_{discharge,opt}$, kW. It shows when and with what intensity the battery should be discharged to cover the load or shave peaks.

The optimized state of charge of the ESS at the end of each time interval t – SoC_{opt}, kWh. This variable tracks the battery charge level and shows its dynamics.

The optimized value of exceeding the contractual power limit from the grid at time t – $P_{penalty,opt}$, kW. This variable is auxiliary, but its optimized values show how successfully the model avoided penalties, or how many excesses had to be allowed at the lowest cost.

To minimize operational costs, an objective function was used to optimize the total operational costs of the seaport for electricity over the entire planning horizon. This function is the sum of three main cost components that arise during each time interval t and are summed over the entire period T:

$$MinF_{\cos t} = \sum_{t=1}^{T} (C_{grid}(t) \cdot P_{grid}(t) \cdot \Delta t + \\ + C_{\deg} \cdot E_{charge}(t) \cdot \Delta t + C_{penalty} \cdot P_{penalty}(t) \cdot \Delta t),$$

where: $C_{grid}(t) \cdot P_{grid}(t) \cdot \Delta t$ – this term represents the cost of electricity that the port purchases from the centralized grid during time interval t. The model aims to buy less energy when tariffs are high and more when they are low, shifting consumption to more favorable periods.

$C_{deg} \cdot E_{charge}(t) \cdot \Delta t$ – this term accounts for the "wear and tear" of the battery during its charging process. Frequent charge-discharge cycles lead to battery degradation, reducing its efficiency and lifespan. Including this term encourages the model to use the ESS rationally, avoiding excessive cycling when the economic benefit does not justify accelerated degradation.

$C_{penalty} \cdot P_{penalty}(t) \cdot \Delta t$ – This term accounts for penalties imposed for exceeding the contractual power limit drawn from the grid. Including this component ensures that the model will actively work to shave peak loads by using ESS or reallocating other energy sources to stay within the contractual power limits.

For adequate model implementation, it is necessary to introduce constraints – a set of mathematical equalities and inequalities that limit the space of feasible solutions. They ensure that the optimized variables comply with physical laws, technical capabilities of equipment, operational rules, and contractual obligations. Without constraints, the optimizer could find unrealistic or physically impossible solutions (e.g., infinite battery discharge or negative consumption).

The power balance constraint is a fundamental limitation that ensures energy conservation. For each time interval t, the sum of all energy sources must equal the total load of the port. This equality guarantees that demand is always met by supply, and every kilowatt of energy is accounted for.

$$P_{load}(t) = P_{grid}(t) + P_{RES}(t) + P_{discharge}(t) - \\ - P_{charge}(t), \quad \forall t \in \{1, \ldots, T\},$$

where $P_{load}(t)$ – total port load,
$P_{grid}(t)$ – power from the grid,
$P_{RES}(t)$ – power from renewable sources,
$P_{discharge}(t)$ – power discharged by ESS,
$P_{charge}(t)$ – power consumed by ESS (charging).

The ESS charge dynamics constraints describe how the battery charge level changes from one time interval to the next, taking into account incoming (charging) and outgoing (discharging) energy, as well as process efficiency.

For the first time interval ($t = 1$):

$$SoC(1) = SoC_{initial} + \\ + \eta_{charge} \cdot P_{charge}(1) \cdot \Delta t - \frac{P_{discharge}(t)}{\eta_{discharge}} \cdot \Delta t,$$

where $SoC_{initial}$ – initial charge level, known parameter.

For subsequent time intervals ($t \in \{2, \ldots, T\}$)

$$SoC(t) = SoC(t-1) + \\ + \eta_{charge} \cdot P_{charge}(t) \cdot \Delta t - \frac{P_{discharge}(t)}{\eta_{discharge}} \cdot \Delta t.$$

Each current $SoC(t)$ depends on the SoC of the previous interval $SoC(t-1)$, as well as the charging and discharging volumes in the current interval, taking into account efficiency η.

Next, we introduce a constraint on exceeding the power limit from the grid. This constraint is crucial for managing penalties. It ensures that the auxiliary variable $P_{penalty}(t)$ will be positive only when the power drawn from the grid $P_{grid}(t)$, exceeds the contractual limit $P_{grid,\max}$.

$$P_{grid}(t) - P_{penalty}(t) \le P_{grid,\max}(t),$$
$$\forall t \in \{\ \{1,\ldots,T\}.$$

Due to the high cost of $C_{penalty}$ in the objective function, the model will strive to make $P_{penalty}(t)$ zero, if possible, i.e., $P_{grid}(t) \le P_{grid,\max}$. If this is not possible (e.g., due to a very high load), $P_{penalty}(t)$ will take the minimum necessary value, reflecting the amount of the overshoot.

Here's the English translation of the provided text:

To limit the range of variables, additional conditions are introduced, ensuring that all powers and states of charge are non-negative.

$$P_{grid}(t) \ge 0;\quad P_{charge}(t) \ge 0;\quad P_{discharge}(t) \ge 0;$$
$$P_{penalty}(t) \ge 0.$$

Also, the charging and discharging power cannot exceed the established maximum values:

$$P_{charge}(t) \le P_{charge,\max};\quad P_{discharge}(t) \le P_{discharge,\max}.$$

The battery's state of charge must always remain within permissible limits to avoid damage and ensure efficient operation:

$$E_{batt,\min} \le SoC(t) \le E_{batt,\max}.$$

Together, the objective function and the system of constraints form a complete mathematical model which, when solved using MATLAB, allows for finding the optimal strategy for managing energy flows in a seaport.

A functional diagram for the mathematical model of electricity demand optimization with the integration of energy storage systems for a seaport is presented in Fig. 1. It shows how various system components interact and what data and energy flows exist.

The Inputs block contains all static and dynamic data fed into the mathematical model. This includes forecasts (load, RES generation), tariff plans, ESS technical specifications, and grid limits. This data forms the basis for formulating the objective function and constraints.

The Optimization Model is the core of the system, where the computational process takes place. Here, the optimization goal is defined – minimizing total costs. All mathematical constraints, which ensure physical authenticity and compliance with regulatory requirements, are integrated into this block.

The Decision Variables (Outputs of Optimization) block displays the main results of the optimization model. These variables are the "decisions" that the model proposes to minimize costs. They show how energy should be distributed throughout the day.

In the Outputs and Analysis block, the received results are processed and interpreted.

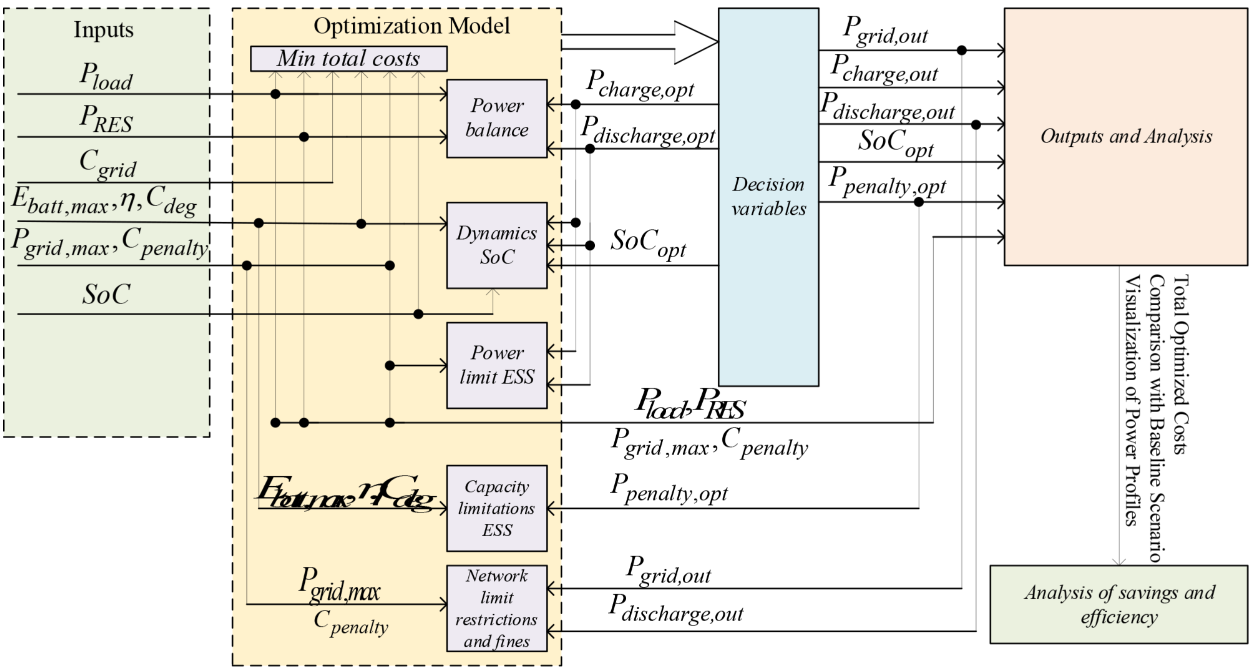

Fig. 1. Functional diagram for the mathematical model

Based on the conducted analysis, final conclusions regarding the feasibility of model implementation and specific recommendations for further actions are formulated. This functional diagram visually explains the flow of information and the interaction of components within the mathematical model, from input data to final conclusions.

Discussion of the Obtained Results. Modeling electricity demand optimization with the integration of energy storage systems for a seaport in MATLAB yielded four key graphs that visualize the behavior of the energy system.

Figure 2 shows the different components of power consumption and generation throughout the day. "Port Load" (blue line) is the basic electricity consumption profile of the port, reflecting its operating schedule with characteristic peaks and troughs. For example, we see an increase in load during daylight hours and a decrease at night. "RES Generation" (orange line) represents electricity production from renewable sources (e.g., solar panels), typically peaking during daylight hours. "Grid Purchase (Opt.)" (green line) is the optimized power profile that the port purchases from the centralized power grid after applying the model and integrating ESS. "Grid Limit" (red dashed line) indicates the contractual power limit that the port can consume from the grid.

From the graphs in Figure 2, the following conclusions can be drawn: the green line ("Grid Purchase (Opt.)") often runs below or close to the red dashed line ("Grid Limit"), especially during peak port load hours. This indicates that the optimization system successfully shaves peak loads, minimizing grid consumption during expensive periods. The graph demonstrates that RES generation is actively used to cover part of the load. Optimized grid purchase (green line) decreases when RES generation (orange line) is high. The port still depends on the external grid, especially during periods of low RES generation or high load when ESS cannot fully cover demand. However, this dependence becomes more manageable and economically viable.

Figure 3 details how the energy storage system interacts with the port's energy system. "ESS Charging" (blue line) shows periods when the battery actively accumulates energy. "ESS Discharging" (orange line) reflects moments when the battery releases stored energy to cover the port's load. The "smart" charging/discharging strategy indicates that ESS charging typically occurs during periods of low electricity tariffs (e.g., at night) or when there

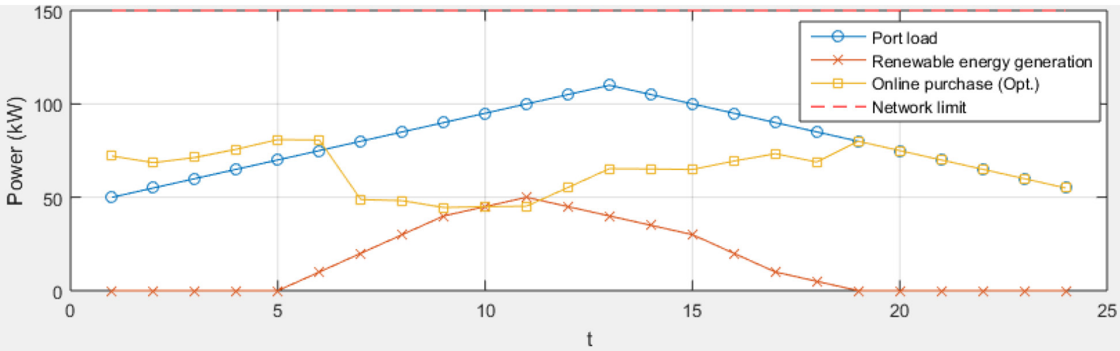

Fig. 2. Power profiles

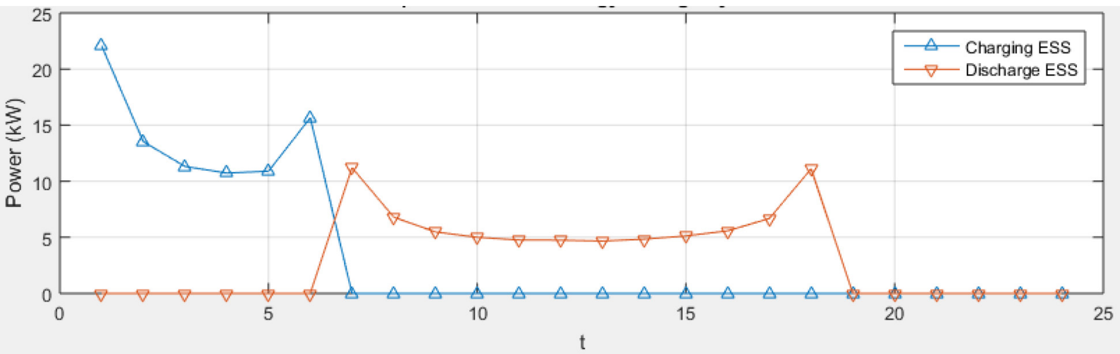

Fig. 3. Operation of the energy storage system

is surplus generation from RES. Discharging, on the other hand, occurs when tariffs are high or when a port's peak load needs to be covered. This demonstrates effective energy arbitrage and peak shaving functionality. As can be seen from Fig. 3, ESS operation helps to smooth the overall grid load, making the port's consumption more uniform, which reduces infrastructure strain and potential penalties. ESS effectively absorbs fluctuations from RES, charging when solar panels generate more energy than needed and discharging when RES generation is low.

Figure 4 shows the dynamics of the battery's charge level throughout the day. "ESS State of Charge" (blue line) is the actual energy level stored in the battery at a given time. The graph shows that the battery charge level (blue line) always remains within the limits between minimum and maximum capacity, which confirms the correctness of the model and the consideration of physical ESS constraints. If the *SoC* graph demonstrates significant fluctuations between the minimum and maximum levels, it indicates active and efficient utilization of the full available battery capacity for optimization. For example, charging to maximum at night and discharging during the day. Provided there is a cyclicity constraint, the charge level at the end of the day (or other optimization horizon) returns to its initial value, ensuring stable system operation over long periods.

Figure 5 shows a comparison of power purchased from the grid. This graph is the most important for demonstrating the economic feasibility of the project. "Grid Purchase (Baseline)" (black line) is the power profile that the port would purchase from the grid without optimization and without ESS integration (or with minimal RES integration). Here, the port's load peaks are directly reflected in grid purchases. "Grid Purchase (Opt.)" (blue line): The optimized power purchase profile, as in the first graph (Fig. 2). "Grid Limit" (red dashed line): Contractual power limit.

The most obvious conclusion is how significantly lower and smoother the blue line

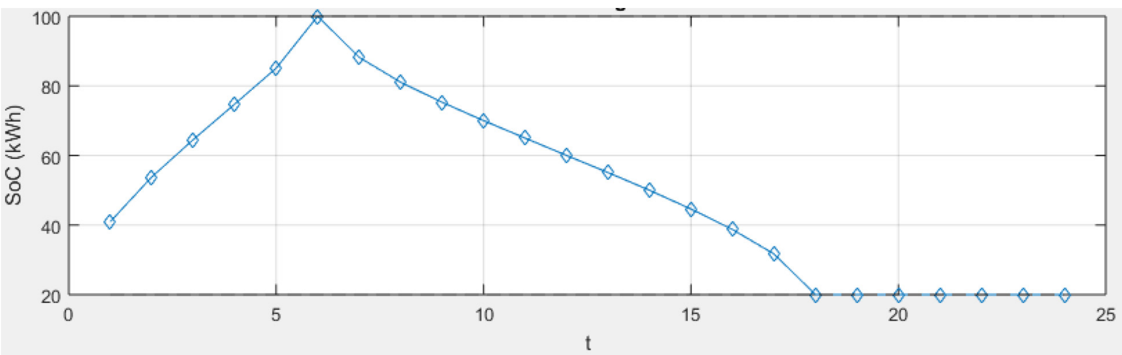

Fig. 4. State of charge ESS

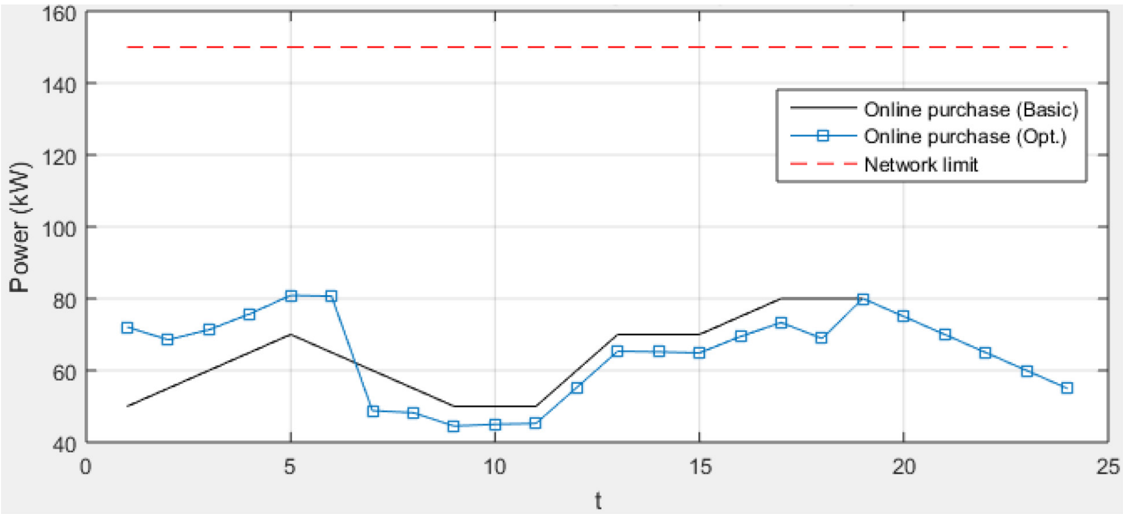

Fig. 5. Comparison of purchasing capacity from the grid

(optimized purchase) is compared to the black line (baseline purchase), especially during periods of maximum port consumption. This means that ESS and RES are effectively used to shave the most expensive power peaks, directly leading to reduced costs for peak tariffs and avoidance of penalties. Increased energy efficiency: A more uniform grid consumption profile indicates more efficient use of the port's energy resources and a reduction in the overall load on the centralized grid. Economic feasibility: The difference between the area under the "Grid Purchase (Baseline)" and "Grid Purchase (Opt.)" curves (considering tariffs) directly reflects the economic savings achieved through the implementation of an intelligent control system and ESS. This graph visually confirms the justification for investment.

Conclusions. The modeling results clearly demonstrate that the integration of energy storage systems and the application of a mathematical optimization model enable a seaport to significantly reduce operational electricity costs. This is achieved through effective peak shaving, optimized utilization of self-generated renewable energy sources, and energy arbitrage (charging during periods of low-cost energy, discharging during high-cost periods). The model confirms an increase in the port's energy resilience and its ability to achieve greater self-sufficiency, which is critically important for uninterrupted logistical operations. These conclusions emphasize the economic and environmental feasibility of implementing such innovative solutions in the energy infrastructure of seaports.

The developed mathematical model for electricity demand optimization with integrated energy storage systems for a seaport has demonstrated its high economic feasibility and significant potential for improving the efficiency and resilience of power supply to port facilities.

Thus, investments in energy storage systems and the development of intelligent control systems are strategically justified for seaports aiming to enhance competitiveness, economic efficiency, and compliance with modern environmental standards. Further research could focus on incorporating aspects of energy trading in local markets and optimizing ESS maintenance into the model.

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