ASSESSING THE TECHNICAL AND ENVIRONMENTAL IMPACTS OF ENERGY MANAGEMENT SYSTEMS IN SMART PORTS

Lappeenranta–Lahti University of Technology LUT

Bachelor's Programme in Electrical Engineering, bachelor's thesis

In co-operation with partner university: Hebei University of Technology

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Professor, Xiaozhen Zhao

ABSTRACT

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This thesis assesses the technical and environmental impacts of Energy Management Systems (EMS) in Smart Ports, with a focus on Shanghai Yangshan Phase IV Port. The thesis begins with a baseline evaluation of EMS implementation and its effects on energy consumption, carbon emissions, and operational costs in Smart Ports. In addition, the thesis examines case studies from four main ports (Hamburg Port, Genoa Port, Jurong Port, and Shanghai Phase IV), assessing their performance based on renewable energy usage, emission reduction rates, and other pertinent factors. Subsequently, technical optimization models were developed to simulate improvements in load dispatch, energy storage, and transport scheduling. An integrated optimization approach then combined these elements to quantify compounded benefits. Results indicate that EMS deployment reduces annual energy consumption and carbon emissions significantly—by approximately 7–8% and 11–12% respectively—while achieving substantial cost savings. The study also identifies critical challenges, including system integration, data quality issues, cybersecurity risks, and the need for standardization.

SYMBOLS AND ABBREVIATIONS

Abbreviations

CO2	Carbon dioxide
EMS	Energy Management System
KPIs	Key Performance Indicators
IEA	International Energy Agency
IoT	Internet of Things
AI	Artificial Intelligence
EU	European Union
LNG	Liquefied Natural Gas
AGV	Automated Guided Vehicle
TEU	Twenty-foot equivalent unit
MSC	Mediterranean Shipping Company
PNRR	National Recovery and Resilience Plan
PCS	Port Community System
BI	Business Intelligence
SMES	Smart Multi-Energy System
NTU	Nanyang Technological University
NUS	National University of Singapore
BESS	Battery energy storage system

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1. Introduction

As the hubs of international logistics, ports are the gateways for the movement of goods and commodities across the globe. As globalization intensifies and the demand for maritime transport grows, ports are experiencing a substantial increase in cargo throughput and ship traffic. This growth, while economically beneficial, brings with it a range of environmental and technological challenges. One of the most pressing concerns is the significant rise in energy consumption and associated greenhouse gas emissions, particularly carbon dioxide, from port operations and associated logistics activities. Addressing these challenges necessitates a shift towards more sustainable and efficient port management strategies. (Moffatt & Nichol. February 3)

Traditionally, ports have relied on conventional operational systems, which often lack the agility, coordination, and technological integration needed to minimize environmental impact. (Pereira, M. T., Rocha, N., Silva, F. G., Moreira, M. Â. L., Altinkaya, Y. O., & Pereira, M. J. 2025) This shortcoming results in energy inefficiencies, underutilization of resources, and a growing carbon footprint. Therefore, it is imperative to adopt innovative solutions that not only streamline port operations but also contribute to environmental sustainability.

In response to these challenges, the concept of Smart Ports has emerged as a transformative paradigm. Smart Ports integrate advanced technologies such as the Internet of Things (IoT), big data analytics, artificial intelligence, and cloud computing into port operations to enhance efficiency, safety, and sustainability (Heilig et al., 2017). A central component of Smart Ports is the Energy Management System (EMS), which plays a pivotal role in monitoring, controlling, and optimizing energy consumption across port facilities. EMS enables real-time data collection and analysis, facilitating informed decision-making and proactive energy-saving measures.

The implementation of EMS in Smart Ports not only improves operational efficiency but also significantly reduces energy waste and CO_2 emissions. By aligning energy demand with supply, automating processes, and integrating renewable energy sources, EMS contributes to the broader goal of environmental sustainability in maritime logistics (Chen, Jihong & Huang, Tiancun & Xie, Xiaoke & Lee, Paul & Hua, Chengying. (2019)).

This research will conduct a systematic analysis of EMS and its integral role in the development of Smart Ports. It will explore the technological and environmental impacts of EMS, examine real-world case studies of successful EMS implementation, and identify the practical challenges associated with its deployment. The aim is to provide a comprehensive reference for academic research and practical strategies in the field of sustainable port management.

2. Literature Review

2.1. Introduction to Energy Management System

EMS is an integrated setup combining advanced hardware and software to monitor, control, and optimize energy consumption. It aims to brush up energy efficiency, lower resource costs, and reduce carbon emissions, thereby supporting sustainable development goals. Nowadays, EMS has become a key solution in addressing global environmental challenges and promoting energy transition. Widely implemented across industrial, commercial, construction, and port sectors, it plays a vital role in enabling data-driven decision-making and facilitating low-carbon operations, especially in the context of Smart Ports where real-time energy management is crucial (International Energy Agency, 2021).

2.1.1 Composition

EMS includes some core component elements like data collection and monitoring, data analysis and decision support, strategy development and optimization as well as user interface and reporting system. EMS could make use of smart sensors and measuring instruments to promptly monitor energy consumption data different equipment and systems and ensure the accuracy of data. According to Sensorfact (Sensorfact. 2023), a standard monitoring system can save no less than 15% of energy cost. Regarding data analysis and decision supporting, EMS can present energy consumption trend forecasting, anomaly detection and recommendation program by data analysis tools and algorithms. Some studies have shown that instruments which applied EMS can recognize the abnormal energy consumption to reduce the unessential energy waste (Frank, E, 2024). Based on the result of analysis, EMS can propose energy saving strategies and recommendations and conduct performance evaluations by Key Performance Indicators (KPIs). It will form a closed-loop feedback mechanism for dynamic optimization. Finally, EMS also supplies a user-friendly interface, which allows manager can easily check and understand data as well as generate reports for review and decision-making.

2.1.2 Market status

According to some data presented by Global Energy Management System Market Report (Inkwood Research. 2024), the global EMS market reached 9.2 billion dollars in 2021 and was projected to reach $35.2 billion by 2030 with an annual growth rate of over 16.2%. This growing trend may stem from several factors. For instance, increasing industrial automation, stricter government regulations on energy efficiency and emissions, growing corporate demand for carbon footprint reduction, and the rising integration of renewable energy sources. Additionally, the volatility and continuous rise of global energy prices have prompted businesses to seek smarter ways to optimize their energy use.

EMS plays a crucial role in managing rising energy costs by enabling real-time monitoring, identifying inefficiencies, and automating energy-saving measures. Through data analytics and predictive insights, EMS allows operators to adjust energy consumption based on demand, reduce peak load charges, and make informed decisions about energy sourcing, thereby significantly lowering operational costs.

2.1.3 Significance

It is essential that implementing an Energy Management System (EMS) for modern businesses and organizations striving to improve sustainability and operational efficiency. EMS integrates monitoring, control, and optimization technologies to improve energy performance, reduce waste, and lower overall operational costs. It supports data-driven decision-making by providing real-time insights into energy usage patterns, helping managers adjust strategies promptly to allocate energy more efficiently.

A typical example of EMS implementation can be found in the hospitality sector. In 2007, the JW Marriott Hotel adopted the ISO 50001-certified EMS, specifically aimed at managing its energy consumption across lighting, HVAC, and other electricity-driven services. Over three years, the hotel improved its energy performance by 16.5%, leading to a cost saving of approximately $471,891 (Integrity Energy, 2024). In this case it presents us how EMS can significantly reduce operational costs by identifying inefficiencies and optimizing energy use across different systems.

Besides helping save money, Energy Management Systems (EMS) greatly assist in alleviating environmental concerns. Operational systems within industrial and commercial facilities covered by EMS are reported to have the potential to optimize energy usage and decrease greenhouse gas emissions by 15 to 25%—primarily from the electricity and fuel consumed (Piekarski & Grübel, 2024). This includes managing energy from grid electricity, natural gas, and renewable energy systems.

Pertaining to Smart Ports, EMS has become of greater importance. Ports are energy-dense centers where complex machinery, logistics systems, and buildings are all intensely energy consumers. Using EMS allows port authorities to track energy usage in real time, mitigate peak load charges, and elevate overall equipment effectiveness. This translates into decreased operating costs and improved sustainability objectives. Smart Ports employ EMS to integrate renewables, off-peak weekday power usage scheduling, emission reduction, and overall to become more robust and future-ready to soar energy prices and climate crises.

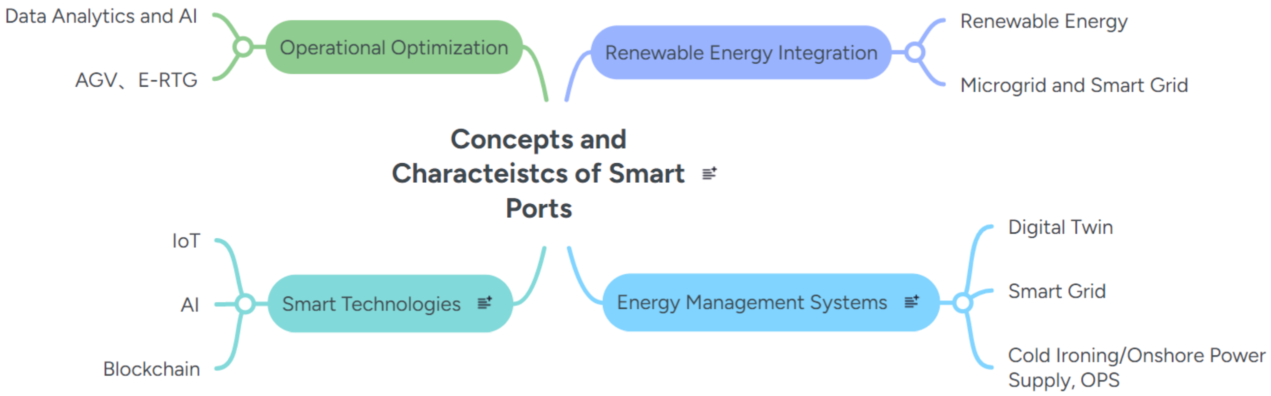

Figure 1. Concepts of Smart Port

2.2 Concept and development of Smart Ports

2.2.1 Definition of a Smart Port

A **Smart Port** refers to a technologically advanced port that leverages digital innovations such as the Internet of Things (IoT), Artificial Intelligence (AI), Cloud Computing, and Big Data Analytics to enhance operational efficiency, optimize resource allocation, and promote environmental sustainability. According to Heilig, Schwarze, and Voss (2017), smart ports integrate these digital technologies to improve port automation, data-driven decision-making, and overall performance. The main goal is to build intelligent, connected, and resilient port infrastructures capable of coping with the increasing complexities of global trade and logistics.

As defined by the International Association of Ports and Harbors (IAPH), a Smart Port is *"a port that uses automation and innovative technologies, including sensors and real-time data, to improve performance while minimizing environmental impact."* These digital transformations not only boost operational productivity but also support strategic goals such as reducing emissions, increasing safety, and improving service quality (IAPH, 2020).

A Smart Port will possess some characteristics like digital infrastructure, automation and intelligence, on top of that sustainable development. It should adopt sensors, smart devices and open data platforms with a high degree of interconnectivity for real-time data collection, transmission and analysis. By using unmanned technologies and automated equipment (e.g.

automated container terminals) increase operational efficiency and reduce labor cost and operational risks. In addition, incorporate environmental protection concepts to minimize the environmental burden through effective energy management and resource optimization.

2.2.2 Growing trend

Several key factors will drive the development of Smart Port. On the one hand, a constantly increasing of international freight traffic induces ports promote their operational efficiency to meet the requirement of growing demand for cargo. Projected to 2030, the world port containerized cargo throughput may reach 27,819.2 million tons (Tok, V. 2022). On the other hand, with the rapid development of IoT, 5G, AI and big data technologies, the digital transformation of smart ports is becoming more and more realistic. As previously mentioned, to face the challenges of climate change, global governments have drawn up stricter environmental protection policy that forces ports adopt some initiative to shrink their emissions. Studies have shown that smart ports can reduce carbon emissions by 30-50 per cent through the introduction of shore power, new energy sources and green infrastructure (Issa-Zadeh, B., Esteban Perez, M. D., López-Gutiérrez, J. S., & Fernández-Sánchez, G. 2023). Then, the requirement also became an important factor, which promotes Smart ports' development. Customers are increasingly demanding fast, efficient and transparent logistics services, and smart ports meet these demands through real-time data sharing and supply chain optimization to enhance customer experience.

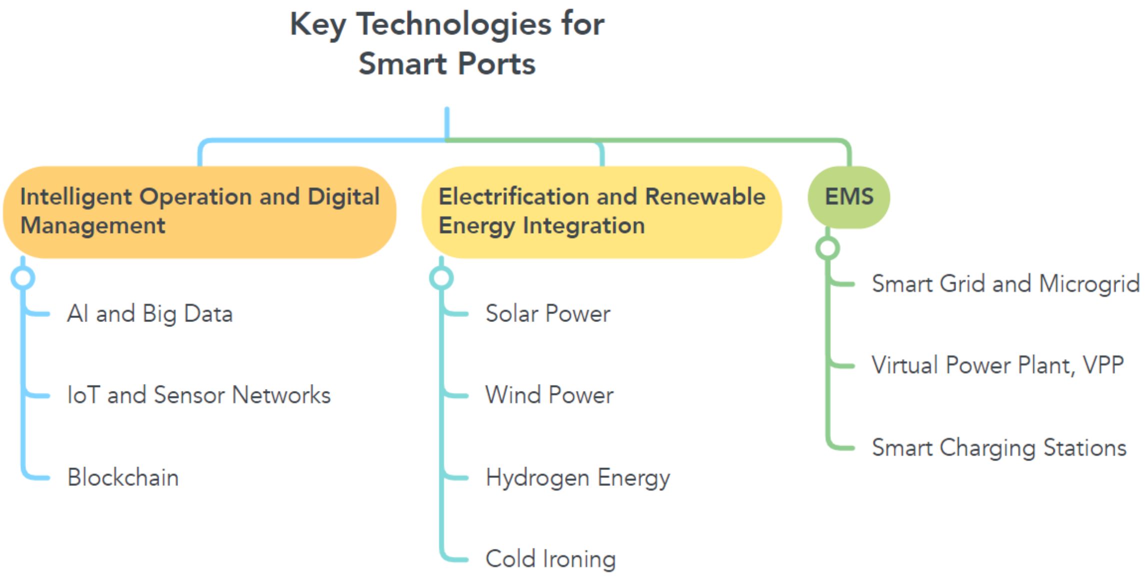

Figure 2. Key technologies of Smart Ports

2.2.3 Key technologies

A variety of today's advanced technologies support the implementation of smart ports.

IoT in Smart Port: IoT in smart ports facilitates the automation of cargo handling, warehousing and logistics processes. Guided by IoT sensors and systems, automated cranes can efficiently load and unload containers from ships (Niko. 2023).

AI: Artificial Intelligence is a key technology for smart ports and the key to port automation. Artificial Intelligence has already impacted global logistics companies and will continue to influence the shipping industry. AI uses powerful algorithms to transform data and replicate human thought processes. Due to the redundancy of port operations, a large amount of historical and real-time data is generated that can be fed into these AI algorithms and technologies (Sinay. 2021).

Blockchain: The application of blockchain can ensure the transparency and security of Smart Ports’ system, which makes this technology become increasingly important in supply chain management, helping to improve the efficiency of information sharing between parties and reducing the risk of deception.

2.3 Energy Management Systems in Smart Ports

The integration of Energy Management Systems (EMS) in Smart Ports plays a crucial role in addressing the dual challenge of high energy consumption and greenhouse gas emissions. EMS helps ports improve their overall energy performance by enabling real-time monitoring, intelligent analysis, and optimized control of energy usage across various systems and equipment. Through these functions, EMS not only contributes to lowering operating costs but also supports the port's sustainability goals by minimizing environmental impact.

Ports rely heavily on electricity to power cranes, lighting systems, cargo handling machinery, and administrative buildings. Inefficient electricity usage can lead to significant energy waste and unnecessary emissions, especially when electricity is derived from fossil fuel-based grids. EMS allows ports to monitor real-time electricity consumption, identify peak demand periods, and schedule energy-intensive activities during off-peak hours. This not only reduces energy costs but also lowers the associated carbon footprint, particularly when combined with renewable energy integration. The key EMS-supported techniques in Smart Ports include:

Shore Power (Cold Ironing): Shore power systems allow docked ships to connect to the port’s electrical grid, enabling them to shut off their onboard diesel generators. This reduces fuel consumption and cuts emissions such as CO_2, NO_x, and particulate matter during berth time.

Real-Time Electricity Monitoring and Control: EMS deploys sensors to track electricity consumption from various equipment including cranes, conveyor belts, and automated guided vehicles. Managers can quickly detect anomalies, identify inefficiencies, and implement corrective actions, such as replacing outdated machinery or redistributing workloads to balance electrical loads.

Intelligent Scheduling and Logistics Optimization: By forecasting power demand and analyzing historical usage patterns, EMS supports optimized scheduling of vessel movements, cargo loading/unloading, and internal transport. This ensures that electricity is used more effectively across operational timelines, reducing both peak loads and idle consumption.

3. Analyzing EMS implementation in Smart Ports from real-life case studies

3.1 Hamburg Port

3.1.1 Sustainability and Efficiency Initiative in Hamburg Port

Hamburg Port is a leading European logistics hub, integrates advanced EMS and port intelligence to achieve sustainability and operational efficiency. The EMS of Hamburg Port is driven by the smartPORT energy strategy, focusing on three pillars: renewable energy integration, energy efficiency optimization, and green mobility transformation (Hamburg Port Authority, 2019).

The renewable energy integration of Hamburg Port focuses on shore power, solar and hydrogen. Since 2016, the port has pioneered shore power infrastructure, enabling ships to switch off diesel engines and connect to renewable energy while docked. By 2030, all major berths will be equipped with shore power, aligning with the EU’s FuelEU Maritime directive. In 2023, the port supplied 1,420 GWh of shore power, significantly reducing emissions (Hamburg Port Authority, 2019). The use of solar and hydrogen energy is reflected in distributed solar panels (8.5 MW capacity) generate over 800 MWh annually, while plans for hydrogen infrastructure aim to meet 70% of Germany’s hydrogen import needs by 2030 (Hamburg Port Authority, 2025).

EMS of Hamburg Port achieve energy efficiency optimization by predictive AI, smart grids and digital twins. Predictive AI aims to analyses equipment data to pre-emptively address inefficiencies by machine learning, which cutting operational costs by up to 40% (Hamburg Port Authority, 2025). Smart Grids and Digital Twins will make real-time monitoring via IoT sensors and digital twins optimizes energy distribution and predicts maintenance needs, reducing energy waste (Hafen Hamburg, 2025).

To implement green mobility transformation, Hamburg Port has chosen the electric equipment, LNG and hydrogen fuels. C. Steinweg Terminal introduced a fully electric reach stacker (SANY SRSC45E5), reducing CO_2 emissions by 70 tons annually and lowering noise pollution (WorldCargo News. (2025, February) Port Technology. (2025, February)). LNG bunkering services and future hydrogen-powered locomotives further decarbonize port operations (Hamburg Port Authority, 2019).

3.1.2 Digitalization and Smart Port Solutions in Hamburg Port

In the area of port intelligence and digitalization, Hamburg's smartPORT framework combines digital technologies and data-driven solutions to enhance logistics and infrastructure management.

Port of Hamburg achieves smart traffic management with IoT sensors and multimodal co-ordination. Over 300 road sensors monitor traffic flows, bridge conditions, and vehicle weights, feeding data into the smartPORT App for optimized routing and congestion reduction. An intermodal PortTraffic Center integrates sea, rail, and road transport data, improving cargo flow efficiency by 20%.

The application of digital twins and automation is reflected in infrastructure and self-service systems. Some critical infrastructure, such as the Köhlbrand Bridge, will make use of virtual modelling technology to enable real-time structural health monitoring and predictive maintenance (Hafen Hamburg, 2025). Autonomous systems, such as remote-controlled cranes and AGVs, minimize human intervention while boosting precision.

The application of EMS in Hamburg Port has had a significant impact on the local environment and economy. The port's carbon intensity dropped to 6.6 kg per TEU in 2023 (35% reduction since 2020)6. Shore power alone eliminated 1,000 tons of CO_2 from LNG bunkering and 6,500 tons from solar energy (Port Technology. (2025, February)). Automated systems increased crane productivity to 57.4 moves per hour, with throughput exceeding 20,000 TEUs daily (Hamburg Port Authority, 2019). Moreover, partnerships with MSC and Maersk of green supply chains aim to establish green methanol bunkering by 2024, aligning with global decarbonization goals.

3.2 Genoa Port

3.2.1 Sustainability and Efficiency Initiatives at Genoa Port

Genoa Port is a leading Mediterranean logistics hub, integrates advanced EMS and port intelligence to enhance sustainability, operational efficiency, and competitiveness. Genoa's EMS focuses on renewable energy integration, energy efficiency, and decarbonization, aligning with Italy's Recovery and Resilience Plan (PNRR) and EU sustainability goals.

Distinct with Hamburg Port, renewable energy integration of Genoa Port is reflected in the three areas of solar energy, smart grids and vehicle electrification. Regarding solar power, Genoa Port has installed distributed solar plants (e.g., 8.5 MW capacity) to power lighting systems, buildings, and its electric vehicle fleet. These installations generate over 800 MWh annually, reducing CO_2 emissions by 6,500 tons (Ports of Genoa, 2023). A hybrid energy grid optimizes renewable energy distribution across terminals, balancing supply with the high energy demands of port operations (Ports of Genoa, 2023) Issa-Zadeh, B., Esteban Perez, M. D., López-Gutiérrez, J. S., & Fernández-Sánchez, G. (2023)). Vehicle electrification refers to the transition from traditional fossil fuel equipment to electric cargo handlers and port vehicles, such as reach stackers, has reduced diesel dependency and cut CO_2 emissions by 70 tons annually at terminals like C. Steinweg.

Genoa Port adopted some measures to increase the efficiency of energy. Like Hamburg Port, Genoa Port also make use of digital twins to build virtual models of port infrastructure, which enable real-time monitoring of energy consumption and predictive maintenance, reducing waste and downtime (Inland Port Areas for Optimal Networks Management in Genoa: From Planning Issues to Artificial Intelligence (2023)). At the same time, by machine learning algorithms analyzing energy usage patterns, the port can optimize equipment performance and energy allocation, achieving cost savings of up to 40%.

On decarbonization goals, PNRR had funded with €35 million, this initiative aims to phase out fossil fuels, reduce carbon intensity by 35% by 2025, and establish Italy's first sustainable port energy hub (Ports of Genoa, 2025).

3.2.2 Digitalization and Port Intelligence at Genoa Port

Genoa Port leverages port intelligence and digitalization to streamline operations and enhance decision-making. The port's main applications are Digital Infrastructure, Automation and AI as well as Smart Traffic and Logistics.

Digital infrastructure includes Port Community System (PCS) and Business Intelligence (BI). PCS is embodied in a paperless platform integrates stakeholders (shipping lines, customs, etc.) for seamless data exchange, accelerating cargo clearance and reducing administrative delays (BIOS Management, 2025). While BI platform synthesizes financial and operational data, enabling scenario simulations and strategic planning (BIOS Management, 2025).

As previously mentioned, automation and AI are used in remote-controlled equipment and predictive maintenance. Automated cranes and Automated Guided Vehicles (AGVs) minimize human intervention while increasing precision in container handling. Meanwhile AI systems forecast equipment failures and optimize maintenance schedules, reducing operational disruptions.

Smart transport and logistics are realized through IoT sensors and multimodal integration. Over 300 sensors monitor traffic flows, bridge conditions, and cargo movements, feeding data into the smartPORT App for real-time route optimization and congestion management. A centralized digital platform coordinates sea, rail, and road transport, improving cargo flow efficiency by 20% (Inland Port Areas for Optimal Networks Management in Genoa: From Planning Issues to Artificial Intelligence (2023).

The application of the above measures and technologies has had a positive impact on the environment and economy of Genoa Port. Solar and electrification initiatives have cut annual CO_2 emissions by over 7,000 tons, with further reductions targeted through hydrogen and wind energy integration (Ports of Genoa, 2025). Automation has increased crane productivity to 57.4 moves per hour, supporting a daily throughput of 20,000 TEUs. The BI platform reduced financial reporting effort by 30%, which enhanced decision-making agility and Economic Resilience (BIOS Management, 2025).

3.3 Jurong Port

3.3.1 Sustainability and Efficiency Initiatives at Jurong Port

Jurong Port is Singapore's premier multi-purpose port, has emerged as a global leader in integrating advanced Energy Management Systems (EMS) and port intelligence to achieve operational efficiency, sustainability, and digital transformation. Jurong Port's EMS focuses on optimizing energy consumption, integrating renewable energy, and reducing carbon emissions through innovative technologies and partnerships.

Jurong Harbor's renewable energy integration includes Singapore's unique AI-Driven Smart Multi-Energy System (SMES), in addition to solar energy, which has appeared before. The port operates a 9.5 MWp solar power system across warehouse rooftops, generating over 12 million kWh annually—meeting 60% of its electricity demand and reducing CO_2 emissions significantly (Li, G.; Wang, T.; Zhou, B.; Xiao, Z.; Yan, S.; Liu, B. 2023, 3, 1). SMES, a system unique to Singapore, which developed with NTU Singapore and SP Group, this system optimizes energy generation from renewables (e.g., solar, LNG) and thermal storage. It dynamically selects energy sources based on demand, achieving 10% energy savings and 15% carbon reduction (Disruptive Tech News. (2024, June 14)).

Jurong Port increases its energy efficiency by smart grid and predictive maintenance. Real-time monitoring via IoT sensors and edge devices (e.g., Anacle's Tesseract smart meters) tracks energy usage across the 155-hectare facility, enabling predictive adjustments to reduce waste (Anacle Systems. (2021, January 14)). While AI algorithms analyze equipment data to preempt failures, minimizing downtime and optimizing energy consumption for cranes, AGVs, and cooling systems (Cash Platform. (2024, June 14), Disruptive Tech News. (2024, June 14)).

In the context of the Green Port Initiatives, Jurong Port aims to phase out fossil fuels by 2025, supported by a S$35 million investment under Singapore's Recovery and Resilience Plan (PNRR) (Cash Platform. (2024, June 14)).

3.3.2 Digitalization and Port Intelligence at Jurong Port

Jurong Port enhances decision making through port intelligence and digitalization. This includes a digital twin platform (JP Glass) as well as AI and IoT Applications. The port also focuses on collaborative innovation.

JP Glass in Jurong Port in the form of integrated operations and 3D visualization. Built on Esri’s ArcGIS, JP Glass consolidates real-time data on vessel movements, cargo types, warehouse occupancy, and personnel activities. It provides interactive dashboards for monitoring berth status, weather conditions, and equipment efficiency. While 3D visualization means this platform’s evolution into a 3D digital twin enables advanced simulations, such as cargo stacking optimization and vessel cross-section analysis, improving turnaround times by 20%.

Jurong Port applies AI and IoT to autonomous systems, traffic and resource optimization. Autonomous systems remote-controlled cranes and AGVs reduce manual intervention, while AI algorithms optimize cargo handling sequences and storage allocation (Cash Platform. (2024, June 14), Maritime Institute. (2024)). Over 300 IoT sensors monitor traffic flows and bridge conditions, feeding data into the smartPORT App for route optimization and congestion management (ESR Singapore. (2024)).

The port is also actively engaged in collaborative innovation. Collaborating with NUS and industry partners (C4NGP Partnership), Jurong Port is developing a digital twin for next-gen port systems, focusing on resource optimization and predictive analytics for its 2025 transformation into a Next Generation Multipurpose Port (Maritime Institute. (2024)).

Jurong Port's EMS applications and intelligence also make an outstanding contribution to the local environment and economy. In terms of Carbon Reduction, Jurong Port's Solar and electrification initiatives cut annual CO_2 emissions by 7,000+ tons, with further reductions planned through hydrogen integration (Li, G.; Wang, T.; Zhou, B.; Xiao, Z.; Yan, S.; Liu, B. 2023, 3, 1, Cash Platform. (2024, June 14)). AI-driven systems increased crane productivity to 57.4 moves/hour, supporting daily throughputs exceeding 20,000 TEU. The SMES project reduced energy costs by 10%, while predictive maintenance lowered equipment downtime by 40%.

3.4 Shanghai Port

The most representative port in Shanghai is the automated terminal of Shanghai Yangshan Deepwater Port Phase IV. As the world's largest and most advanced fully automated container terminal, Yangshan Phase IV serves as a flagship project in China's smart port development. Its Energy Management System (EMS) and cutting-edge automation technologies integrate sustainability, efficiency, and innovation. Yangshan Phase IV’s EMS is a cornerstone of its green transformation, combining renewable energy integration, smart grids, and AI-driven optimization.

The integration of renewable energy in Yangshan IV is reflected in the application of solar energy, LNG refueling and shore power. Rooftop solar panels with 8.5 MW capacity generate over 8 million kWh annually, covering 30% of the terminal’s energy demand and reducing CO_2 emissions by 6,500 tons/year. Meantime, as a global LNG bunkering hub, the terminal provides ship-to-ship LNG refueling services via the Hai Gang Wei Lai (20,000 m^3 capacity), reducing vessel emissions by 1,000 tons annually. Furthermore, all berths are equipped with high-voltage shore power systems, supplying 1,420 GWh annually to docked ships, eliminating black carbon and NOx emissions.

In terms of energy efficiency measures, Yangshan Phase IV adopts AGV Battery Swap System and AI-Driven Load Balancing. AGVs automatically swap depleted batteries at designated stations (6 minutes per swap), reducing downtime and energy waste. This system slashes energy consumption by 40% compared to diesel-powered alternatives. Machine learning algorithms optimize energy distribution across equipment (cranes, AGVs, lighting) based on real-time operational demands.

The port also utilizes a smart grid and digital twin. A hybrid smart grid dynamically balances energy supply from solar, grid power, and storage systems. In addition, a digital twin platform simulates energy flows and equipment performance, enabling predictive maintenance and reducing unplanned downtime by 25%.

The environmental and operational performance of Yangshan IV is remarkable, with Carbon intensity dropped to 6.6 kg CO_2 per TEU in 2023 (35% reduction since 2020). Crane productivity reached 57.4 moves/hour, a world-leading figure. With a throughput of 20,000+

TEUs per day and 24/7 operation. Labor costs reduced by 70% due to automation, while energy savings exceed $2 million annually.

3.5 Comparative Analysis

The table below presents a comparative overview of the EMS adopted by the four example Smart Ports: Hamburg Port, Genoa Port, Jurong Port, and Shanghai Yangshan Phase IV. It highlights key performance indicators such as the share of renewable energy, emission reductions achieve, and cost savings enabled through the deployment of smart technologies. In addition, the table outlines how each port schedules its energy demand, the primary renewable sources utilized, and the core technologies underpinning their EMS frameworks. Energy storage solutions and grid flexibility measures are also examined, offering insights into the infrastructure supporting these ports' decarbonization strategies. Furthermore, the table details their long-term sustainability targets, alignment with national or regional policy frameworks, and the measurable impact of automation on port operations. This comparative analysis provides a clear snapshot of the diverse approaches taken by leading ports worldwide in advancing operational efficiency, climate resilience, and energy sustainability through intelligent and integrated energy systems.

Category	**Hamburg Port**	**Genoa Port**	**Jurong Port**	**Shanghai Yangshan Phase IV**
Renewable Energy (%)	23.5% (2023)	40% (2023)	60% (2023)	48.8% (2023)
Emission Reduction (%)	38% (2020–2023)	35% (2020–2023)	15% (2020–2023)	10% (2020–2023)
Cost Reduction via Smart Devices (%)	40% (AI-driven optimization)	30% (digital twins & BI platform)	10% (SMES & IoT sensors)	30% (AGV battery swap system)
Energy Demand Scheduled (%)	20% (smartPORT App)	22.4% (Port Community System)	48.4% (JP Glass digital twin)	30% (ITOS system)

Key Renewable Sources	Shore power, solar, hydrogen	Solar, hybrid grids	Solar, LNG, thermal storage	Solar, LNG, shore power
Core Technologies	Digital twins, predictive AI	AI analytics, electrified AGVs	AI-driven SMES, 3D digital twin	AGV battery swap, digital twin
Energy Storage	Hydrogen storage (planned)	Battery storage	Thermal storage	Battery storage
Grid Flexibility	Smart grids	Hybrid grids	IoT edge devices	Smart grids
Decarbonization Targets	Climate neutrality by 2040	35% carbon reduction by 2025	Fossil-free by 2025	50% RE share by 2030
Policy Alignment	EU FuelEU Maritime Directive	Italy’s PNRR Recovery Plan	Singapore Green Plan 2030	China’s Dual Carbon Goals
Automation Impact	20% cargo flow efficiency gain	20% faster cargo clearance	20% turnaround time reduction	70% labor cost reduction

Table 1. Comparison of Energy Management Systems (EMS) in Major Global Ports (Data comes from Welt. (2024). Jiangsu Provincial Department of Ecology and Environment. (2024, January 15). Yahoo Finance. (2024). HHLA. (2024). ScienceDirect. (2019). Nanyang Technological University. (2024). PSA BDP. (2024). European Commission. (2024). European Commission. (2024). World Bank, 2025). Port of Hamburg, 2024). Notteboom, T., & Haralambides, H. (2023). Munisamy, S., & Singh, G. (2011). Ruca Logistics. (2024, December 26).)

The reasons for the differences between the different ports will be analyzed next. Differences and the reasons behind them will be presented.

3.5.1 Difference in share of renewable energy

This part presents the percentage of renewable energy usage of the four example Smart Ports. It is obvious that Jurong Port takes the lead in this respect. Genoa Port and Shanghai Yangshan IV have about 40% and 50% renewable energy use, respectively, while Hamburg

Port has the least, at about 23%, which is about one-third that of Jurong Port. Considering the difference in port sizes, the actual difference could be even larger.

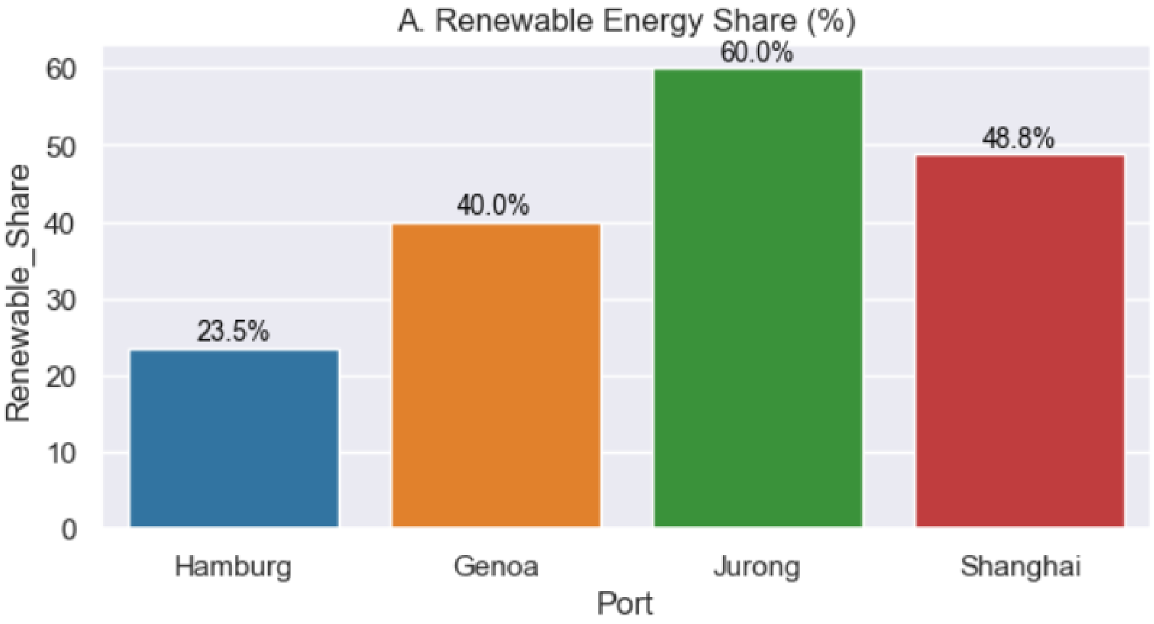

Figure 3. Renewable energy share

Port	**Renewable Energy (%)**	**Key drivers**	**Restraint**
Hamberg Port	23.5	- EU Hydrogen Strategy promotes investment in hydrogen infrastructure - Full coverage of shore power systems (FuelEU Maritime policy support)	- Limited light resources and low solar potential in northern Germany - Commercialization of hydrogen energy will take time
Genoa Port	40%	- Italian PNRR funding supports solar and hybrid grids - Mediterranean region is rich in light	- Limited harbor space for large-scale deployment of wind power - Slow progress in modernizing the electricity grid
Jurong Port	60%	- Singapore's small size maximizes rooftop solar use - SMES system integrates multiple energy sources (solar + LNG)	- High land costs make it difficult to expand offshore wind - Challenges of high temperature and high humidity environments on the efficiency of energy storage systems

Shanghai Yangshan Phase IV	48.8%	- China's 'Dual Carbon' Targets Drive LNG and Shore Power Adoption - Scale up PV deployment	- Coal-dependent energy mix limits renewable energy share - High throughput leads to a large energy demand base

Table 2. Proportion of renewable energy use and influencing factors among ports

In this table, it shows that regional resources and policy priorities will observably influence renewable energy using in these ports. For instance, the high percentage of solar power used in Genoa and Jurong Port benefit from their geographical conditions. While Hamburg Port relies on policy-driven hydrogen energy.

3.5.2 Percentage difference in emission reductions

The following bar chart shows the emission reduction percentage of the four ports. In this respect, Jurong Port and Shanghai Yangshan Phase IV, which were leading the pack, are instead lagging in the figures. Hamberg Port and Genoa Port did better this time, although they still failed to break 40 per cent. It is worth noting, however, that unlike the renewable energy percentage, the emission reduction percentage is a year-on-year comparison. For example, Jurong Port was already doing very well in terms of emissions reductions, so it has more limited room to fall, which results in a lower percentage value.

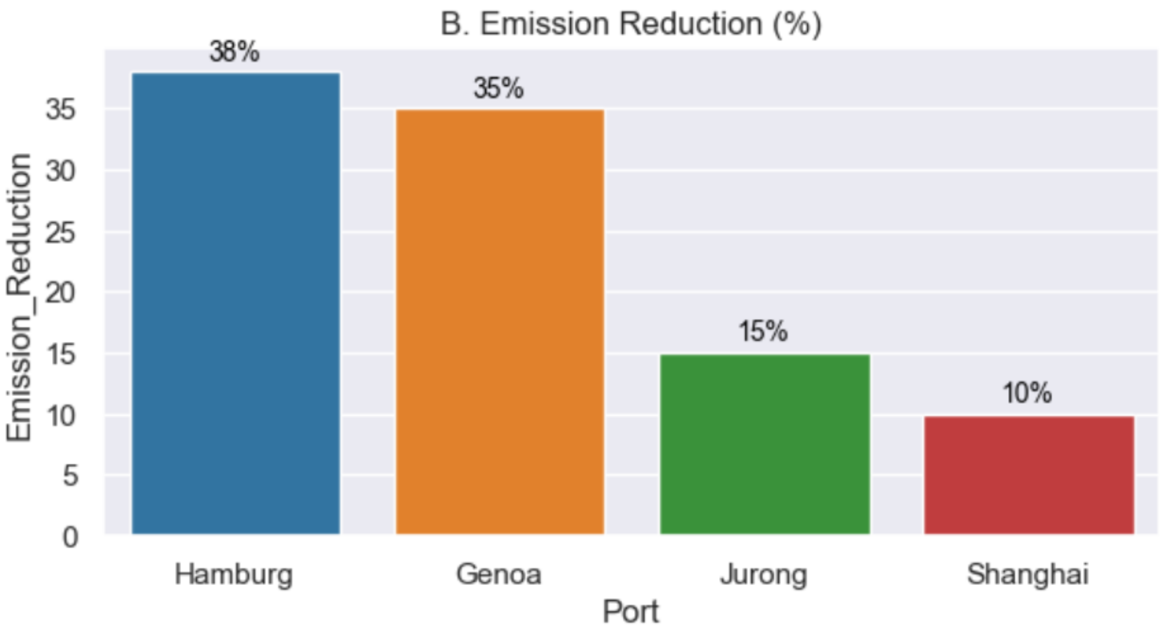

Figure 4. Emission reductions

Port	Emission Reduction (%)	Main measures	Baseline for emission reduction potential
Hamberg Port	38%	- Shore power to replace fuel oil for ships - Electric forklift trucks and hydrogen-powered locomotives	High initial emissions (reliance on traditional energy sources), large scope for emission reductions
Genoa Port	35%	- Solar power and vehicle electrification - Digital logistics to reduce empty transport	Italy's ports had low original energy efficiency; policy drives rapid improvement
Jurong Port	15%	- Efficient SMES system optimizes energy distribution - Ladder energy storage utilizing decommissioned batteries	Singapore's ports are already highly energy efficient (a global leader), with increasing marginal abatement costs
Shanghai Yangshan Phase IV	10%	- AGV battery quick-change system (40 per cent reduction in energy consumption) - LNG cold energy recycling	High thoughts result in a large emissions base, but automation technology dramatically improves efficiency

Table 3. Emission reduction ratios and influencing factors among ports

The table shows that emission reduction ratio may cause distinction by base line and technology path. A low emission reduction ratio doesn't mean that Jurong Port has less emission reduction. It's because it starts from a much higher base. In contrast, other ports achieve significant emission reductions by replacing traditional energy sources. Therefore, they have a similar proportion of emission reductions. In terms of technology, Shanghai and Hamburg through hardware innovations (AGV/LNG), Genoa and Jurong focusing on software optimization (digital platform).

3.5.3 Percentage difference in cost reduction

This table shows the percentage cost savings for the four Smart Ports. As with the previous percentage reductions, this is still a year-by-year comparison of percentage values. So, whilst Jurong Port still has the lowest percentage, this is still because it has already done so much in this area that the room for decline is limited. Apart from it, Hamburg Port has a cost saving ratio of 40%, while Shanghai Yangshan Phase IV and Genoa Port have the same ratio (30%). Of course, due to the difference in volume, the former's total cost reduction is greater than the latter.

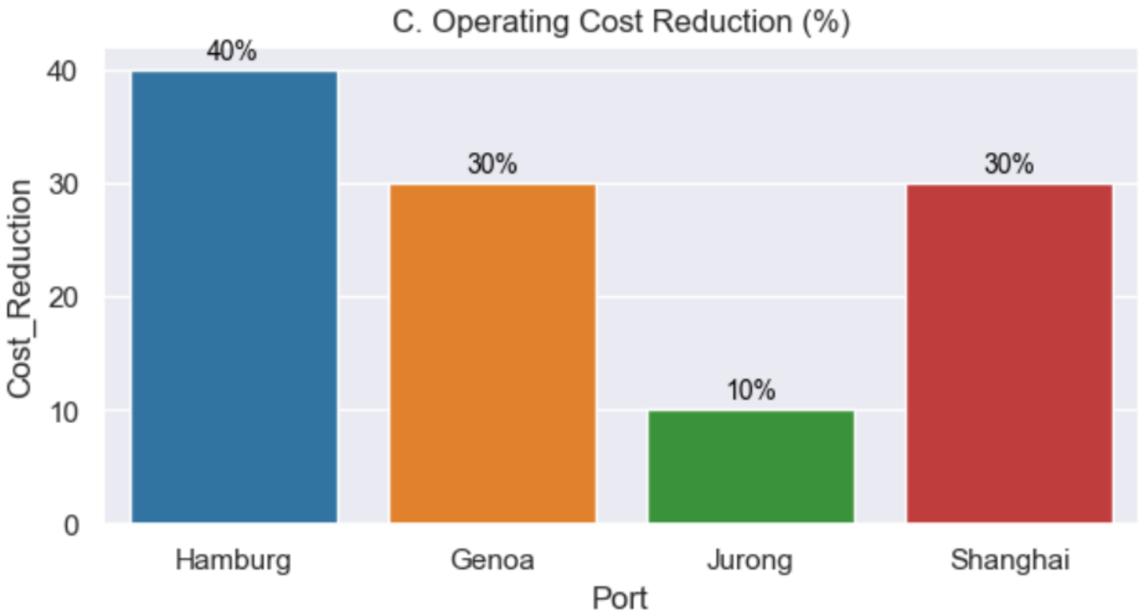

Figure 5. Cost reduction

Port	**Cost reduction (%)**	**Core Technology**	**Economic drivers**
Hamberg Port	40%	- Predictive AI reduces equipment maintenance costs - Long-term cost advantages of hydrogen	The EU carbon tax regime pushes up fossil energy costs, forcing investment in clean technology
Genoa Port	30%	- Port Community System (PCS) to reduce administrative delays - BI Platform Optimizes Purchasing Decisions	High labor costs in Italy, digitalization saves human resources
Jurong Port	10%	- SMES Dynamic Selection of Low-Cost Energy - IoT Sensors Prevent Energy Waste	Singapore's High Energy Prices Prompt Fine-Tuned Cost Management
Shanghai Yangshan Phase IV	30%	- AGV automation reduces labor costs by 70% - Scale up PV to reduce electricity prices	China's Manufacturing Advantage Reduces Equipment Purchase Costs, Supported by Government Subsidies

Table 4. Cost reduction ratio and influencing factors among ports

The main influencing factors of difference in cost reduction are reflected in cost structure differences and policy tools. The conservation in Shanghai Yangshan Phase IV and Hamburg Port mainly come from automation and scale effects. Whereas Genoa and Jurong rely on process optimization. Policy instruments, mainly in the form of carbon taxes in the EU and subsidies in China, will have a direct impact on the rate of return on technology investments.

3.5.4 Differences in the efficiency of energy demand dispatch

In this chart, the scheduling efficiency of the four ports is presented. Clearly, as the world's leading Smart Port, Jurong Port still leads the way in this type of data. And Shanghai Yangshan IV, as an emerging port, also shows efficiency second only to Jurong Port. This has to do with the fact that it is a new port that has been built with a variety of smart scheduling technologies. The Hamberg Port and Genoa Port, which are veteran Smart Ports, performed mediocrely, with only about 20% or so scheduling efficiency

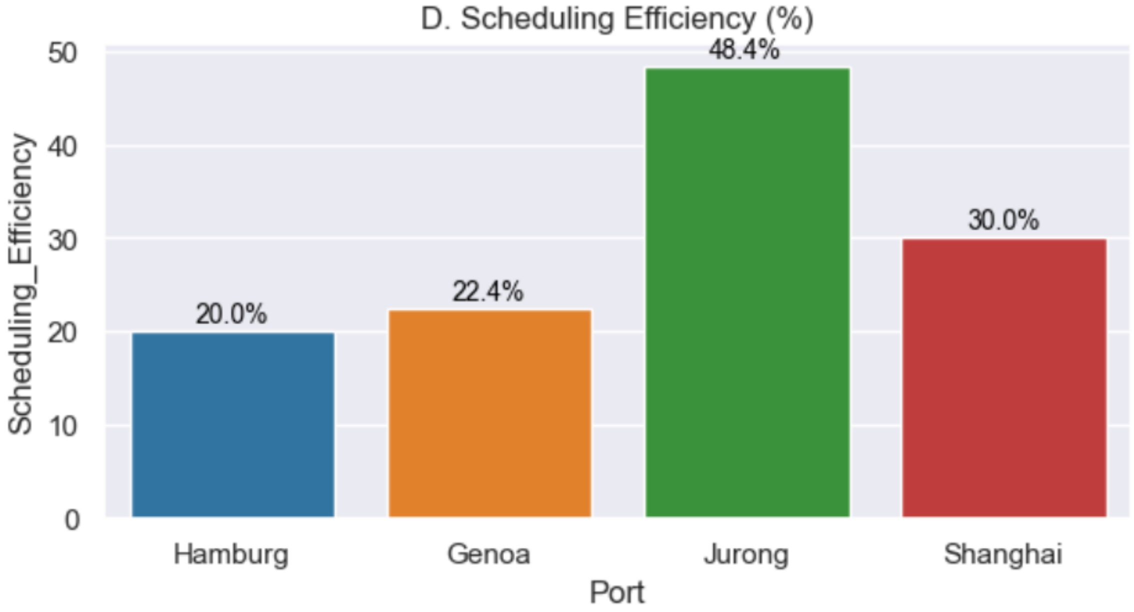

Figure 6. Scheduling efficiency

Port	**Movement control efficiency (%)**	**Technical tools**	**Data integration capabilities**
Hamberg Port	20%	- smartPORT App real-time traffic management - Multimodal transport center to coordinate air, land and sea transport	Limited cross-sectoral data sharing (involving multiple logistics companies)
Genoa Port	22.4%	- Port Community System (PCS) standardized data exchange - AI to predict cargo arrival times	Italian SMEs have varying levels of digitization
Jurong Port	48.4%	- JP Glass 3D Digital Twin Simulation Yard - AI Optimizes Cargo Loading and Unloading Sequences	Singapore's highly centralized port management boosts data synergy
Shanghai Yangshan Phase IV	30%	- Fully automated scheduling of ITOS systems - Digital Twins Predict Equipment Failures	Chinese policy promotes industry-wide data integration (e.g. customs, shipping companies)

Table 5. Movement control efficiency and influencing factors between ports

From the table, it presents centralized management and technology maturity. Shanghai and Jurong applied government-led models to make data integration easier. By contrast, Hamburg and Genoa need to reconcile multiple interests. In terms of technology, the depth of application of digital twins and AI algorithms directly affects the scheduling efficiency cap.

3.5.5 Overall comparison between ports

Combining previous data, we can get a radar chart which presents the comparation among the four ports. In the radar chart, each port is clearly shown in all aspects of what it is doing well and what it is not doing well. For instance, Jurong Port has the most extreme data among these ports. Its percentage of renewable energy sharing and scheduling efficiency are both the highest, which is much higher than the other three. Especially the percentage of renewable energy sharing in Jurong Port, which become the only one data over 60% in this line chart. The exact opposite of that, Hamberg Port is the best performer in terms of emission reduction and operating cost reduction. As Jurong Port, Hamberg Port is also the most prominent of the four ports in these two areas. As for Genoa Port, it's the most average performer across the board. Finally, Shanghai Yangshan Phase IV, as an emerging smart port, is still lacking in various aspects compared to other ports.

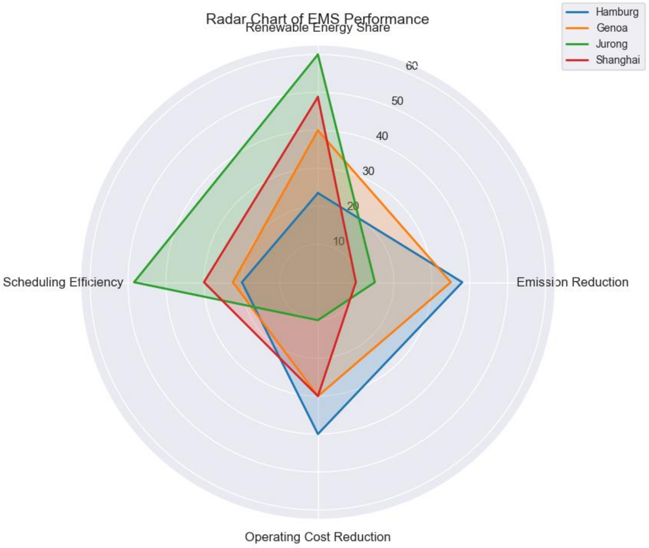

Figure 7. Overall comparison

4. Mathematical modelling

Based on the above research, it is found that due to some confidentiality policies of the Chinese government and companies, the data collected for Shanghai Yangshan Phase IV is less than the other three ports, and most of them are presented in the form of non-precise data ratios. Therefore, this study attempts to collect data from other Smart Ports of similar size to Shanghai Yangshan Phase IV and combines it with the known data of the former and tries to calculate the estimated value of each data of Shanghai Yangshan Phase IV in the form of mathematical model and then assesses its environmental and technological impacts.

4.1 Environmental impact modelling

4.1.1 carbon emission modelling

EMS reduces carbon emissions mainly by optimising energy consumption and introducing cleaner energy sources, and the total carbon emissions can be expressed: (Nextbitt. 2024, November 9)

$$E_{CO_2} = \sum_i (E_i \cdot EF_i)$$

In this equation, E_{CO_2} stands for the total port carbon emissions (kg CO_2), E_i is the consumption of energy $\boldsymbol{i}$ (usually fossil fuels in this equation) and EF_i is Carbon emission factors for the above types of energy (kg CO_2/kWh or kg CO_2/L).

By using EMS, ports can reduce carbon emissions by introducing renewable energy E_{renew} (Jiang, Peng & Huang, Yifan. 2024)

$$E_{CO_2}^{new} = \sum_i (E_i^{new} \cdot EF_i) - E_{renew} \cdot EF_{grid}$$

In this equation, E_{renew} stands for the renewable energy supply (kWh) and EF_{grid} is grid average carbon emission factor (kg CO_2/kWh).

This results in a reduction in carbon emissions:

$$\Delta E_{total} = E_{CO_2} - E_{CO_2}^{new}$$

4.1.2 Energy consumption optimisation model

The total energy consumption of the harbour can be expressed as:

$$E_{total} = E_{equip} + E_{transport} + E_{buildings}$$

In this equation, E_{equip} is energy consumption of equipment such as cranes, automated guided vehicles (AGVs), $E_{transport}$ stands for energy consumption of trucks, container transport and $E_{buildings}$ is energy consumption for port building lighting, air conditioning, etc.

EMS reduces energy consumption by optimising energy use:

$$E_{total}^{new} = E_{equip}^{new} + E_{transport}^{new} + E_{buildings}^{new}$$

Energy Savings Rates:

$$\eta_{save} = \frac{E_{total} - E_{total}^{new}}{E_{total}} \times 100\%$$

4.2 Technology impact modelling

4.2.1 Smart Power Dispatch Optimisation

To describe the problem of port load balancing we can use constraint optimisation (Wikipedia contributors.):

$$min \sum_{t} C(P_t) = \sum_{t} \alpha P_t^2 + \beta P_t + \gamma$$

In this equation, P_t is Port load power at time $\boldsymbol{t}$ (MW), $C(P_t)$ means electricity consumption cost function (usually quadratic) and $\alpha\beta\gamma$ are cost factor.

The EMS then optimizes power distribution through dispatching strategies (such as peak load shaving and valley load filling) so that:

$$\frac{dC}{dP_t} = 0$$

Next, load balancing constraints are performed (Amazon Web Services.):

$$\sum_i P_{i,t} = P_t \ , \forall t$$

Where $P_{i,t}$ is the power requirement of the i-th type of equipment.

4.2.2 Energy storage system optimisation

The harbour uses an energy storage system (BESS) for energy management and the energy storage status is met:

$$E_{BESS,t+1} = E_{BESS,t} + P_{charge,t} \cdot \eta_{charge} - \frac{P_{discharge,t}}{\eta_{discharge}}$$

In this formula, $E_{BESS,t}$ stands for the stored energy of the energy storage system at time t (kWh), $P_{charge,t}$ and $P_{discharge,t}$ means charge and discharge power and η_{charge} and $\eta_{discharge}$ is charge and discharge efficiency.

Charge and discharge are constrained:

$$0 \leq E_{BESS,t} \leq E_{BESS,max}$$

$$0 \leq P_{charge,t} \leq P_{charge,max}, \qquad 0 \leq P_{discharge,t} \leq P_{discharge,max}$$

4.2.3 Intelligent Transport System Dispatch

Optimal scheduling of AGVs (Automated Guided Vehicles) in ports can be modelled as a path optimisation problem (Loem, M. 2020, May 27):

$$min \sum_{i} \sum_{j} d_{ij} x_{ij}$$

Where d_{ij} stands for the distance from point ***i*** to point ***j*** and x_{ij} is the value is 1 if the AGV takes the path, 0 otherwise.

Binding:

$$\sum_{j} x_{ij} = 1, \qquad \sum_{i} x_{ij} = 1$$

This formula ensures that each AGV chooses only one path, minimizing the transportation distance and improving efficiency.

5. Result

By the following section we can get mathematical modelling to optimize the technology and environmental impacts of Shanghai Yangshan Phase IV. According to the calculation, the average energy consumption of Shanghai Yangshan Phase IV will be reduced by more than 17 GWh per year with EMS compared to a port of the same size. Carbon emissions, on the other hand, have been reduced by nearly 30,000 tonnes per year.

The mathematical model in this study evaluates items such as energy consumption, CO2 emissions and Battery Energy Storage System (BESS) in the port of Shanghai Yangshan IV by integrating various modules. The approximate environmental and technological impacts are estimated by combining existing data with approximate port data.

5.1 Energy Consumption and CO_2 Emissions

Utilizing data from Shanghai's Yangshan Phase IV terminal, the code calculates baseline energy consumption based on a throughput of 6.3 million TEUs and a unit energy consumption of 125 kWh/TEU, resulting in a total of 787,500 MWh. This consumption is allocated among equipment (50%), transportation (30%), and buildings (20%). Applying emission factors of 0.5, 0.7, and 1.2 kg CO_2/MWh respectively, the initial CO_2 emissions amount to 590,625 kg CO_2. Incorporating 10% renewable energy usage (78,750 MWh) with a grid emission factor of 0.4 kg CO_2/MWh reduces emissions by 31,500 kg CO_2, highlighting the environmental benefits of renewable integration. According to available data, the energy saving rate of the Shanghai Yangshan IV port is about 10 per cent. The total energy consumption will therefore be reduced to 708,750 MWh.

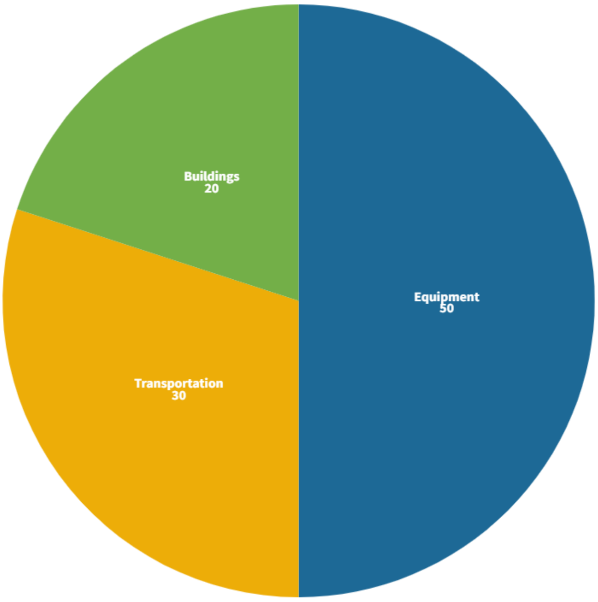

Figure 8. Distribution of energy consumption

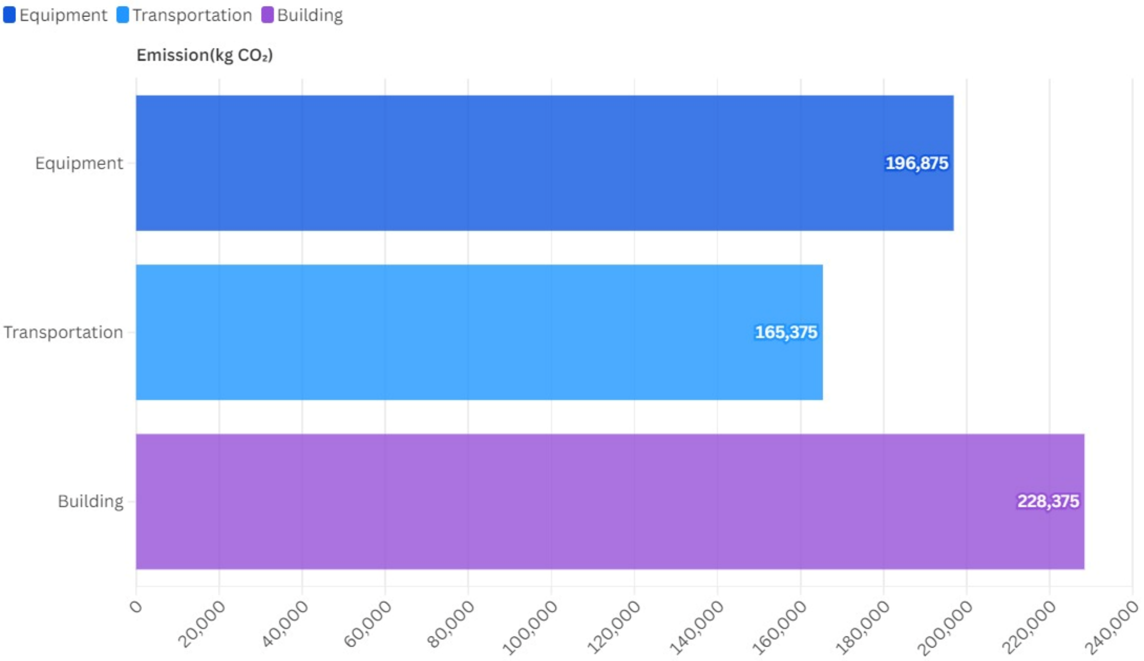

Figure 9. Distribution of carbon emissions by equipment type

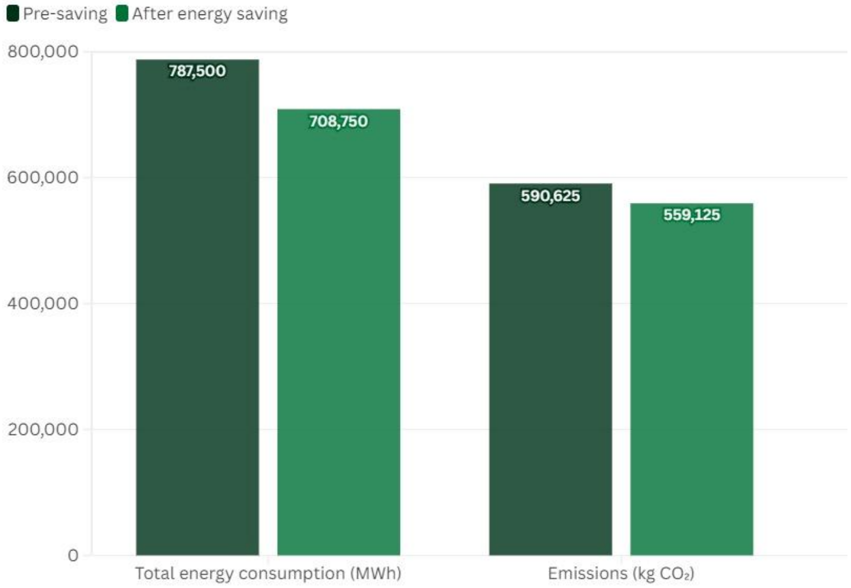

Figure 10. Total energy consumption before and after energy saving

5.2 Load Distribution Optimization

The mathematical model uses optimisation techniques are employed to minimise the operational costs associated with load allocation. For a three-cycle single-load scenario with initial power requirements of 0.4, 0.5 and 0.6 MW and cost coefficients α = 0.0001, β = 0.5, and γ = 5.0, the optimisation produces an optimal load allocation that minimises the total cost. In a multi-device environment with two devices and power requirements of 0.9, 1.1 and 1.3 MW, the optimal allocation ensures that each cycle is met at the lowest cost, emphasising the role of EMS in cost-effective load management.

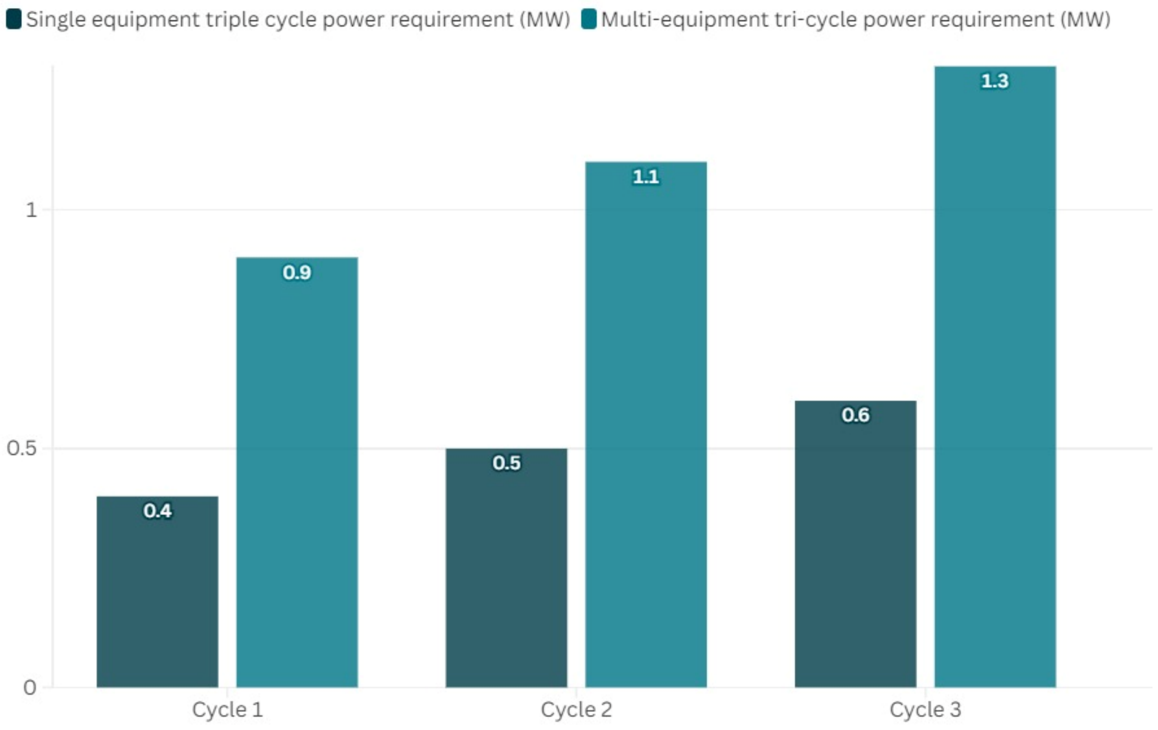

Figure 11. Comparison of power requirements per cycle

5.3 BESS, AGV route optimisation and cost analysis

The ESS module simulates three cycles of charging and discharging, considering an initial storage of 15 MWh, a maximum capacity of 40 MWh, a maximum charging/discharging power of 8 MW, and an efficiency of 88%. Optimisation ensures efficient energy storage utilisation, balancing charging and discharging to support load demand while maintaining system constraints. A Hungarian algorithm is applied to optimise AGV routing between nodes in major ports. Using a distance matrix that represents the distance between nodes (e.g. 35 km between nodes A and B), the algorithm determines the optimal allocation that minimises the total distance travelled, thus improving the efficiency of logistics within the port.

Finally, operating costs were assessed on the basis of a throughput of 6.3 million TEUs, with baseline and optimised costs set at $250 and $175 per TEU, respectively. This resulted in a total cost reduction of $472.5 million, or 30 per cent. These figures highlight the significant economic advantages of implementing EMS optimisation in port operations.

	Node A	Node B	Node C
Node A	0	35 km	40 km
Node B	35 km	0	20 km
Node C	40 km	20 km	0

Table 6. AGV Path Planning with the Hungarian Algorithm

Metric System	Baseline	Optimization	Amount of savings
Cost per TEU	$250	$175	-$75
Total cost (6.3 million TEU)	$1,575 million	$1,102.5 million	-$472.5 million (down 30 per cent)

Table 7. Cost Comparison

6. Discussion

6.1 Current deficiencies in EMS

The main shortcomings of EMS in Smart Ports are reflected in conflict with maritime transport in traditional ports, reliance on data quality and availability as well as network security risk. Firstly, the conflict between EMS in Smart Ports and traditional ports is manifested in multiple dimensions such as energy and systems. As shown in the above bar charts, EMS has already made Smart Ports a clear step up from traditional ports in terms of sustainability. But most of Smart Ports kept a high reliance of fossil fuel, which can be presented by the percentage below 50%. On the systems side, integrating EMS with existing port systems (like legacy software, industrial control systems) can be complex and costly. This can lead to deployment delays and potential data incompatibility. Second is reliance on data quality and availability, as EMS in Smart Ports clearly relies more on high-quality, real-time data from sensors and IoT devices than traditional harbour systems that have been around for a long time. Incomplete or inaccurate data can undermine the effectiveness of the system. This can significantly reduce the accuracy of optimisation and decision-making in Smart Ports. Finally, network security risk and increased digitisation also means that EMSs with their EMS and connected devices are more likely to be potential targets of cyberattacks and less robust. This can lead to service interruptions, financial losses and security compromises.

6.2 Possible challenges

About the challenges, firstly, there is still a lack of standardisation of Smart Ports for EMS applications. There are currently no universally accepted standards or protocols that enable EMS integration across different ports and regions. In this case, interoperability between Smart Ports will be limited and the solution will be difficult to scale. This raises the question of how Smart Ports will scale up in the future to meet the growing demand. As trade volumes increase, EMS must deal with larger, more complex data sets. Without proper scaling, performance bottlenecks and system inefficiencies may occur. In addition, the current pace of iteration of AI, IoT and renewable energy solutions may also challenge the EMS framework. This requires Smart Port to continue to invest in R&D and system upgrades to keep up with technology iterations. Finally, Smart Ports operators also need to pay close attention to national and international environmental regulations and standards in order to quickly adapt and comply with new policies and achieve sustainability goals.

6.3 Response programme

To address the above shortcomings and challenges, a combination of technology and strategy is required. The poor interoperability of Smart Port can be solved by modular system design. Building an EMS platform with standardised interfaces and modular architecture can simplify integration and upgrades. For network security, the use of strong encryption, network segmentation and real-time monitoring are used to prevent network threats. And there is a strong focus on developing an adaptive and scalable infrastructure to ensure that hardware and software can evolve with port throughput and technological advances.

7. Conclusion

This research demonstrates that implementing Energy Management Systems in Smart Ports can lead to notable improvements in operational efficiency, environmental sustainability, and cost-effectiveness. The case study about four typical Smart Ports (Hamburg Port, Genoa Port, Jurong Port and Shanghai Yangshan Phase IV) present about 40% of average renewable energy share, 25% of average emission reduction percentage, 28% of average cost reduction and 30% of scheduling efficiency improvement.

In addition, Shanghai Yangshan Phase IV Port illustrates that baseline EMS implementation already yields considerable reductions in energy use and carbon emissions (more than 700,000 MWh energy reduce and 30 tons CO2 emission reduction), and that technical optimizations further enhance these benefits. Integrated strategies that combine smart dispatch, advanced storage solutions, and intelligent transport scheduling not only optimize resource allocation but also achieve more than 472.5 million dollars of cost reduction.

However, the study also underscores challenges such as data integration complexities, cybersecurity vulnerabilities, and the absence of universal standards for EMS integration. Future research should focus on addressing these challenges, exploring scalable solutions, and examining the long-term impacts of EMS advancements in diverse port environments. Overall, the findings contribute to the broader understanding of sustainable port management and offer practical recommendations for the global shipping industry’s move toward greener, smarter operations.

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Appendix

1. Graphs

```
import pandas as pd
import matplotlib.pyplot as plt
import seaborn as sns
import numpy as np

sns.set_theme()

ports = ["Hamburg", "Genoa", "Jurong", "Shanghai"]
metrics = ["Renewable_Share", "Emission_Reduction", "Cost_Reduction", "Scheduling_Efficiency"]
titles = [
    "Renewable Energy Share",
    "Emission Reduction",
    "Operating Cost Reduction",
    "Scheduling Efficiency"
]

data = {
    "Renewable_Share": [23.5, 40, 60, 48.8],
```

```
    "Emission_Reduction": [38, 35, 15, 10],
    "Cost_Reduction": [40, 30, 10, 30],
    "Scheduling_Efficiency": [20, 22.4, 48.4, 30]
}

df = pd.DataFrame({"Port": ports, **{k: v for k, v in data.items()}})

port_colors = {"Hamburg": "#1f77b4", "Genoa": "#ff7f0e", "Jurong": "#2ca02c", "Shanghai": "#d62728"}

fig, axes = plt.subplots(2, 2, figsize=(18, 12))
fig.suptitle("Comparison of Key EMS Metrics for Ports", fontsize=16)

for i, (metric, title) in enumerate(zip(metrics, titles)):
    ax = axes[i // 2, i % 2]
     bars = sns.barplot(x="Port", y=metric, data=df, ax=ax, palette=[port_colors[p] for p in df["Port"]])
    ax.set_title(title, fontsize=12)
    for j, val in enumerate(df[metric]):
        bars.text(j, val + 1, f"{val}%", ha="center", fontsize=10, color="black")

values = df[metrics].values
angles = np.linspace(0, 2 * np.pi, len(metrics), endpoint=False).tolist()
values = np.concatenate((values, values[:, [0]]), axis=1)  # Close the radar chart
```

```
angles += angles[:1]  # Close the radar chart

fig, ax = plt.subplots(figsize=(8, 8), subplot_kw={"projection": "polar"})
ax.set_theta_offset(np.pi / 2)
ax.set_theta_direction(-1)
ax.set_xticks(angles[:-1])
ax.set_xticklabels(titles)

for i, (port, color) in enumerate(port_colors.items()):
    ax.plot(angles, values[i], label=port, color=color, linewidth=2)
    ax.fill(angles, values[i], color=color, alpha=0.25)

ax.set_title("Radar Chart of EMS Performance", fontsize=14)
ax.legend(loc="upper right", bbox_to_anchor=(1.2, 1.1))

plt.show()
```

2. Mathematical Model

```
import numpy as np
from scipy.optimize import minimize, linear_sum_assignment

def calculate_E_co2(E, EF):
```

```
    return sum(e * f for e, f in zip(E, EF))

def calculate_E_co2_with_renew(E, EF, E_renew, EF_grid):
    return calculate_E_co2(E, EF) - E_renew * EF_grid

def calculate_delta_E_total(E_co2, E_co2_new):
    return E_co2 - E_co2_new

def calculate_E_total(E_equip, E_transport, E_buildings):
    return E_equip + E_transport + E_buildings

def calculate_E_total_new(E_new):
    return sum(E_new)

def calculate_eta_save(E_total, E_total_new):
    return (E_total - E_total_new) / E_total * 100

# Environmental Impact Assessment
E_equip = 787500 * 0.50
E_transport = 787500 * 0.30
E_buildings = 787500 * 0.20
E = [E_equip, E_transport, E_buildings]
EF = [0.5, 0.7, 1.2]
E_renew = 78750
```

```
EF_grid = 0.4

original_co2 = calculate_E_co2(E, EF)
new_co2 = calculate_E_co2_with_renew(E, EF, E_renew, EF_grid)
delta_co2 = calculate_delta_E_total(original_co2, new_co2)
print("CO₂ reduction:", delta_co2, "kg CO₂")

E_total = calculate_E_total(E_equip, E_transport, E_buildings)
print("Original total energy consumption E_total:", E_total, "MWh")

E_new = [E_equip * 0.9, E_transport * 0.9, E_buildings * 0.9]
E_total_new = calculate_E_total_new(E_new)
print("Optimized total energy consumption E_total_new:", E_total_new, "MWh")

eta_save = calculate_eta_save(E_total, E_total_new)
print(f"Energy saving rate η_save: {eta_save:.2f}%")

def cost_function(P, alpha, beta, gamma):
    return np.sum(alpha * P**2 + beta * P + gamma)

T = 3
P0 = np.array([0.4, 0.5, 0.6])
alpha, beta, gamma = 0.0001, 0.5, 5.0
bounds = [(0, None)] * T
```

```
constraints = []

res = minimize(fun=cost_function, x0=P0, args=(alpha, beta, gamma),
               method='SLSQP', bounds=bounds, constraints=constraints)

if res.success:
    P_opt = res.x
    cost_opt = res.fun
    print("\n[Single Load Scheduling] Optimal load allocation P_opt:", P_opt, "MW")
    print("Corresponding minimum total cost cost_opt:", cost_opt)
else:
    print("\n[Single Load Scheduling] Optimization did not converge, message:", res.message)

def cost_function_multi(P_vars, alpha, beta, gamma, T, N):
    P_matrix = P_vars.reshape(T, N)
    P_total_each_t = np.sum(P_matrix, axis=1)
    return np.sum(alpha * P_total_each_t**2 + beta * P_total_each_t + gamma)

T = 3
N = 2
P_demand = [0.9, 1.1, 1.3]

constraints_multi = []
for t in range(T):
```

```
    def eq_constraint(P_vars, t=t):
        P_matrix = P_vars.reshape(T, N)
        return np.sum(P_matrix[t, :]) - P_demand[t]
    constraints_multi.append({'type': 'eq', 'fun': eq_constraint})

P0_multi = np.array([P_demand[t] / N for t in range(T) for i in range(N)])
bounds_multi = [(0, None)] * (T * N)

res_multi = minimize(fun=cost_function_multi, x0=P0_multi,
                     args=(alpha, beta, gamma, T, N),
                     method='SLSQP', bounds=bounds_multi, constraints=constraints_multi)

if res_multi.success:
    P_opt_vars = res_multi.x
    cost_opt_multi = res_multi.fun
    print("\n[Multi-device Allocation] Optimal total cost:", cost_opt_multi)
    P_opt_matrix = P_opt_vars.reshape(T, N)
    print("Device allocation per time period (rows: time periods, columns: devices):\n", P_opt_matrix)
    for t in range(T):
        print(f"Time period t={t}: Total allocated load = {np.sum(P_opt_matrix[t, :])} MW, Demand = {P_demand[t]} MW")
else:
    print("\n[Multi-device Allocation] Optimization did not converge:", res_multi.message)
```

```
def cost_function_bess(vars_, T, E_bess_max, eta_charge, eta_discharge):
    return 0.0


def define_bess_constraints(T, E_bess_init, E_bess_max, eta_charge, eta_discharge):
    constraints_list = []


    def idx_e(t):
        return t
    def idx_c(t):
        return T + t
    def idx_d(t):
        return 2*T + t


    def init_constraint(vars_):
        return vars_[idx_e(0)] - E_bess_init
    constraints_list.append({'type': 'eq', 'fun': init_constraint})


    for t in range(T - 1):
        def state_eq(vars_, t=t):
            return (vars_[idx_e(t+1)] - vars_[idx_e(t)]
                    - vars_[idx_c(t)] * eta_charge
                    + vars_[idx_d(t)] / eta_discharge)
        constraints_list.append({'type': 'eq', 'fun': state_eq})
```

```
    return constraints_list

T = 3
E_bess_init = 15.0
E_bess_max = 40.0
eta_charge = 0.88
eta_discharge = 0.88
max_charge_power = 8.0
max_discharge_power = 8.0

x0_bess = np.zeros(3 * T)

bounds_bess = []
for t in range(T):
    bounds_bess.append((0, E_bess_max))
for t in range(T):
    bounds_bess.append((0, max_charge_power))
for t in range(T):
    bounds_bess.append((0, max_discharge_power))

cons_bess = define_bess_constraints(T, E_bess_init, E_bess_max, eta_charge, eta_discharge)
```

```
res_bess = minimize(
    fun=cost_function_bess,
    x0=x0_bess,
    args=(T, E_bess_max, eta_charge, eta_discharge),
    method='SLSQP',
    bounds=bounds_bess,
    constraints=cons_bess
)

print("\n[BESS Charging/Discharging Example]")
if res_bess.success:
    sol = res_bess.x
    print("BESS optimization result:", sol)
    E_bess_opt = sol[0:T]
    P_charge_opt = sol[T:2*T]
    P_discharge_opt = sol[2*T:3*T]
    print("E_bess_opt:", E_bess_opt)
    print("P_charge_opt:", P_charge_opt)
    print("P_discharge_opt:", P_discharge_opt)
else:
    print("BESS optimization did not converge:", res_bess.message)

points = ["A", "B", "C"]
cost_matrix = np.array([
```

```
    [np.inf, 35.0, 42.0],
    [35.0, np.inf, 28.0],
    [42.0, 28.0, np.inf]
])
row_ind, col_ind = linear_sum_assignment(cost_matrix)
total_cost = cost_matrix[row_ind, col_ind].sum()

print("\n[AGV Path Optimization]")
print("Optimal assignment:")
for i, j in zip(row_ind, col_ind):
    print(f"From {points[i]} to {points[j]}, distance: {cost_matrix[i, j]} km")
print("Minimum total distance:", total_cost, "km")

print("\n=== Summary Calculations ===")
print(f"Original total CO₂ emissions: {original_co2:.2f} kg CO₂")
print(f"CO₂ emissions after using renewable energy: {new_co2:.2f} kg CO₂")
print(f"CO₂ reduction: {delta_co2:.2f} kg CO₂")
print(f"Original total energy consumption: {E_total:.2f} MWh")
print(f"Optimized total energy consumption: {E_total_new:.2f} MWh")
print(f"Energy consumption reduction: {E_total - E_total_new:.2f} MWh")
print(f"Energy saving rate: {eta_save:.2f}%")
print(f"AGV shortest path total distance: {total_cost:.2f} km")

throughput = 6.3e6
```

```
baseline_cost_per_TEU = 250
optimized_cost_per_TEU = baseline_cost_per_TEU * 0.7

baseline_total_cost = throughput * baseline_cost_per_TEU
optimized_total_cost = throughput * optimized_cost_per_TEU
cost_reduction = baseline_total_cost - optimized_total_cost
print("\n=== Operational Cost Calculation ===")
print(f"Baseline operational cost: {baseline_total_cost:,.0f} USD")
print(f"Optimized operational cost: {optimized_total_cost:,.0f} USD")
print(f"Operational cost reduction: {cost_reduction:,.0f} USD")
print(f"Operational cost reduction rate: {(cost_reduction / baseline_total_cost)*100:.2f}%")
```