1 September 2026

Electrification Pathways for the Port of Singapore

Implications for the global maritime industry

Centre for Strategic Energy and Resources

Final Report

Electrification Pathways for the Port of Singapore: Implications for the Global Maritime Industry

A joint study led by the Centre for Strategic Energy and Resources in collaboration with Shanghai Maritime University and T&E Asia Pacific

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Executive Summary

Singapore, as one of the world's leading transshipment hubs handling around 20 per cent of global container transshipment flows, faces growing pressure to decarbonise its port operations in line with international and national climate commitments. Electrification, encompassing cargo handling equipment, automated vehicles, and onshore power supply, represents a critical pathway to reduce greenhouse gas emissions and air pollutants while strengthening long-term operational efficiency and competitiveness. In collaboration with Shanghai Maritime University and T&E Asia Pacific, this study provides a comprehensive assessment on the costs and benefits of electrifying Singapore ports and proposes structured pathways towards deeper electrification by 2035.

Using a novel hybrid modelling framework that combines Wavelet Transform Coherence, Temporal Convolutional Network, and eXtreme Gradient Boosting, the study builds upon high-resolution historical port activity data to predict future demand and hence energy usage patterns. The framework captures multi-scale fluctuations, operational dependencies, and nonlinear relationships in port energy use, achieving strong predictive performance with high generalisation capability. The study also emphasises that successful electrification is not driven by infrastructure deployment alone, but by a policy–demand–infrastructure sequence in which regulatory signals create demand certainty that enables large-scale investment.

Based on our current assumptions, results indicate that port throughput is projected to increase by approximately 37 per cent between 2026 and 2035. Annual energy demand is expected to rise correspondingly from around 455 GWh to more than 625 GWh, reflecting the close coupling between operational scale and electricity consumption. Yard cranes and automated guided vehicles account for the largest share of demand, highlighting where electrification and efficiency improvements can deliver the greatest impact. Under the Fully Electrified Port (FEP) scenario, peak electricity demand increases sharply to about 789.7 MWh by 2035, compared with around 473.9 MWh under the Reference Scenario, underscoring the importance of forward-looking power infrastructure planning and development as well as demand side management.

From an environmental perspective, full electrification enables the phase-out of diesel use in port equipment by 2035, generating significant reductions in carbon emissions and virtually eliminating local pollutants such as NO_x, SO_x, and particulate matter. Depending on future grid decarbonisation, annual emissions reductions from port equipment alone could reach 68 kt-CO_2 under a constant grid emission factor, or 94 kt-CO_2 under a declining grid emission factor by 2035. Additional gains arise from shore power deployment, which reduces vessel emissions at berth and improves local air quality.

However, shore power also introduces an important policy challenge. Under current global emissions accounting frameworks, emissions from ship auxiliary engines are attributed to the vessel, whereas emissions from shore power electricity are attributed to the host country's power sector. As a result, shore power can shift part of the emissions inventory from ships to Singapore despite lowering total system emissions. This highlights the need for fair and transparent frameworks covering emissions attribution, carbon pricing, and electricity tariff design so that ports are not penalised for supporting maritime decarbonisation.

From an economic perspective, our study finds that the cost of a fully electrified port, in the case of Singapore, might not represent a significant barrier. Depending on the planning approach, our study finds that the cost of achieving full electrification would only lead to a slightly more than doubling of the expected cumulative investment as compared to the Reference Scenario, i.e. from S$1.2 billion (Reference Scenario) to S$2.6 billion if planning based on peak demand; or from S$96.5 million to S$195.7 million if planning based on gradual annual energy demand, both over a 10 year outlook period.

Electrification would also bring cost savings due to increased equipment efficiency and relatively lower cost of electricity as compared to diesel. Based on fuel cost saving alone, port electrification could lead to more than S$190 million cost savings between 2026 and 2035 under full electrification. Even with fuel savings alone, we expect the payback period to be no later than 2030, which has not included savings from maintenance cost for diesel equipment and the sales of electricity to ships through shore power. Additional benefits arise from avoided carbon tax, especially given the expected uprising trajectory of Singapore's carbon tax rates. Factoring the savings due to avoided carbon tax would further reduce the payback period.

Overall, the study concludes that port electrification in Singapore is technically feasible, economically justifiable, and environmentally necessary. Success will depend on coordinated planning across ports and the power system, strong policy signals such as mandates and carbon pricing, innovative financing models, and regional cooperation on standards and green shipping corridors. With its strategic location, advanced infrastructure, and regulatory capabilities, Singapore is well positioned to lead port electrification across Asia-Pacific and establish a replicable model for global maritime decarbonisation.

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1 Background Overview

Singapore, as a global maritime hub handling around 20 per cent of container transshipment, faces growing pressure to decarbonise its port operations. The International Maritime Organisation (IMO) Net-Zero Framework, together with the Maritime and Port Authority of Singapore (MPA) net-zero ambitions, creates a strong impetus for the development of climate-aligned port infrastructure. Electrification of port operations, including cargo handling and logistics, combined with onshore power supply (OPS), has the potential to reduce up to 1.5 million tonnes of annual greenhouse gas emissions, while also significantly lowering air pollutants such as SOx, NOx, and particulate matter associated with fossil fuel use.

However, global experience suggests that infrastructure deployment alone is insufficient to drive decarbonisation. Strong policy and regulatory signals, including mandatory electrification requirements, fuel and emission standards, and carbon pricing, are critical in creating demand, which in turn enables and sustains infrastructure investment. This policy–demand–infrastructure sequence is essential to ensure both the financial viability and scalability of port electrification.

Given Singapore’s strategic position and its advanced port infrastructure, the Centre for Strategic Energy and Resources, in collaboration with T&E, has undertaken this study to assess the decarbonisation and pollution reduction potential of port electrification in Singapore. The study also examines the associated implications for cost, investment, technology adoption, and policy design. Building on these findings, a three-step approach to port electrification is proposed, which can serve as a reference model for ports across the Asia-Pacific region in their transition towards net-zero operations by 2050.

2 Objective and Boundaries of the Study

In this study, we focus on Singapore ports, with Shanghai ports used as a reference for benchmarking and validation. Using a novel modelling approach, the study provides a comprehensive assessment of the costs, benefits, and infrastructure requirements associated with port electrification. It also aims to generate insights into how policy-driven demand creation can shape electrification pathways. The scenarios explored reflect accelerated electrification trajectories beyond current expectations, in alignment with Singapore’s long-term ambition to achieve net-zero emissions for port terminals by 2050.

A hybrid modelling framework is adopted by integrating three artificial intelligence models, trained on high-resolution hourly vessel data over a full year in 2025. The analysis evaluates key metrics, including greenhouse gas emissions, air pollutants, and costs under different electrification scenarios. For onshore power supply, the assessment focuses on container vessels of 400 gross tonnages and above, given their dominant contribution to berthing electricity demand. Ferries and auxiliary vessels are excluded, as they do not typically utilise shore power in the Singapore context. On the port side, the study examines the electrification of key equipment, including cranes and prime movers. The analysis is based solely on publicly available data and information.

3 Methodology

3.1 Modelling Framework

3.1.1 A Hybrid Modelling Approach

Port electricity demand exhibits characteristics such as non-stationarity, temporal correlation, and strong coupling with operational drivers, including vessel arrivals, cargo handling activities, and equipment utilisation. A single modelling approach is often insufficient to simultaneously address signal decomposition, temporal dependency, and complex nonlinear relationships across a diverse set of variables. Therefore, a hybrid modelling framework is proposed, integrating Wavelet Transform Coherence (WTC), Temporal Convolutional Network (TCN), and eXtreme Gradient Boosting (XGBoost) to perform a staged analysis (Figure 3-1).

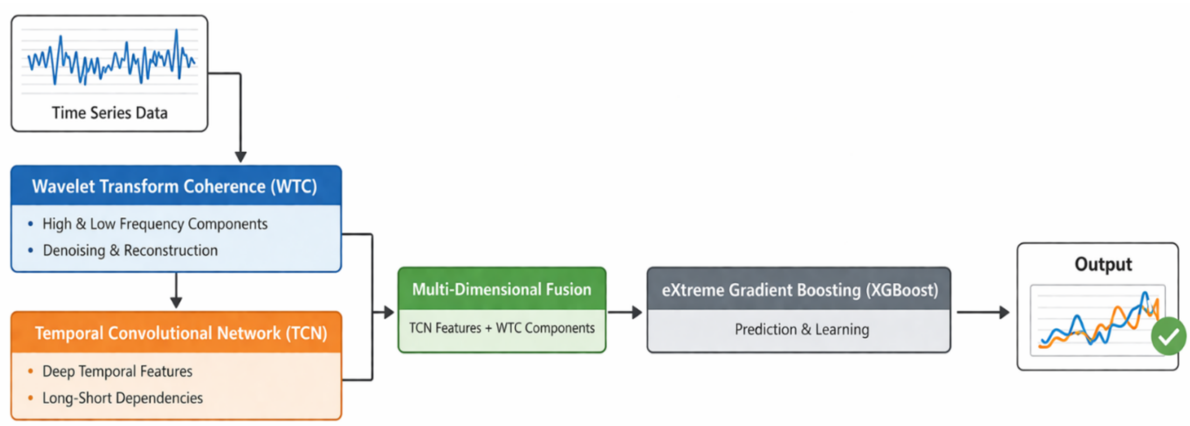

Figure 3-1 Overview of the hybrid modelling framework

This combined approach enables a comprehensive characterisation of port energy demand across multiple time scales, operational scenarios, and equipment states (for example, operating, idling, and charging), thereby improving forecasting accuracy and reliability. While the modelling framework provides a robust basis for estimating energy demand and associated infrastructure requirements, it is important to note that modelling outputs alone do not determine real-world outcomes. The actual trajectory of electrification will ultimately depend on policy signals that shape demand, investment decisions, and implementation pathways.

Sections 3.1.2 to 3.1.4 further elaborate on the characteristics of port energy demand time series data and the specific roles of each model in addressing these characteristics.

3.1.2 WTC: Handling Non-Stationary and Multi-Scale Fluctuations

WTC is designed to address several key characteristics of port energy demand time series data, including:

(1) Pronounced hourly fluctuations
(2) Day-night periodicity
(3) Sudden spikes caused by concentrated vessel arrivals
(4) Localised sharp variations triggered by working hours and equipment operation

Such data can be considered as a 'single's' raw time series that are inherently non-stationary, making them difficult for models such as TCN to learn directly. To address this, WTC is applied in the first stage to decompose the original power demand time series and other key input variables into the following components:

(1) Low-frequency trend
(2) Mid-frequency operational rhythm
(3) High-frequency abrupt fluctuation

This decomposition reduces noise interference and highlights the underlying variation patterns in the data. In other words, WTC's role is to perform 'pre-processing' and 'feature enhancement' for historical port electricity demand data, enabling subsequent models to more clearly identify how the electricity demand changes across OPS, quay cranes, yard cranes, and automated guided vehicles (AGV) due to operational activities.

While WTC improves the accuracy of demand pattern identification and provides a stronger analytical basis for infrastructure planning, such planning must ultimately be aligned with policy-driven demand rather than relying solely on technical projections.

3.1.3 TCN: Modelling Temporal Dependencies and Extracting Dynamic Evolution Patterns

TCN is designed to address the following characteristics of the time series data:

(1) Power demand is continuously influenced by the operational circumstances of the preceding hours.
(2) Vessel berthing, loading and unloading, and departure exhibit clear temporal transmission patterns.
(3) The loads of quay cranes, yard cranes, AGVs, and other equipment show temporal persistence and lagged dependence due to continuous operations and task sequencing.
(4) The load during a given period is often related to similar operational rhythms from the previous day or several previous days.

This indicates that port electricity consumption is not merely a random fluctuation at a single moment, but rather a dynamic time-series process in which short-term fluctuations and long-term dependencies coexist. Relying solely on traditional machine learning methods will be difficult to fully capture such sequential correlations and multi-timescale effects. As such, TCN is chosen to perform temporal modelling on the various sequences after they are decomposed by WTC, and to learn from the dynamic evolution patterns of historical port energy demand data.

TCN will be able to extract the following features:

(1) Short-term continuous fluctuation features
(2) Cross-period cumulative impact features
(3) Periodic repetitive operational features
(4) Temporal coupling features between vessel operations and equipment operations

TCN employs causal convolution to ensure that predictions rely solely on historical information and utilises dilated convolution to expand the receptive field. As a result, it is able to capture not only short-term load variations over recent hours, but also sustained effects arising from vessel operations, equipment usage, and day-night patterns. The temporal modelling of demand also highlights the importance of predictability in electricity consumption patterns, reinforcing the need for regulatory mechanisms that ensure stable utilisation of electrified systems such as OPS.

3.1.4 XGBoost: Fusing Multi-Source Features and Correcting Nonlinear Prediction Errors

XGBoost is designed to address the following characteristics of the time series data:

(1) There are complex nonlinear relationships between load and influencing factors such as the number of vessels, working hours, and equipment operating status
(2) Different end-use equipment, such as OPS, quay cranes, yard cranes, and AGV, influence one another during operation
(3) The sensitivity of electricity demand to operational activities varies significantly across different time periods and levels of operational intensity. Relying only on temporal models often makes it difficult to fully exploit the information contained in structured operational features

Port energy consumption is influenced not only by temporal dependencies, but also by the combined effects of a large number of business variables and operational-state variables. Moreover, the relationships between these variables and the load are often not simply linear.

Although TCN can extract temporal features effectively, it encounters limitations when trying to capture the complex nonlinear mapping relationships among port operational variables. Therefore, XGBoost is introduced to further integrate the temporal features generated by TCN with structured variables such as vessel berthing schedules, working hours, and equipment energy consumption, thereby producing the final predictions or correcting residual prediction errors.

In brief, XGBoost primarily performs the following functions:

(1) Identifies nonlinear relationships between multiple operational features and load
(2) Integrates temporal features with tabular features
(3) Corrects TCN prediction bias associated with sudden fluctuations and local errors
(4) Improves the overall forecasting accuracy and stability of the model

Specifically, XGBoost incrementally optimises prediction results by integrating multiple decision trees. It is well suited to handling high-dimensional features, feature interactions, and nonlinear mapping problems. Therefore, it is particularly appropriate for the comprehensive modelling of variables such as vessel operation intensity, equipment operating status, and disaggregated energy consumption in port environments. Ultimately, it serves as a fusion and correction module within the combined model, further improving the accuracy of future port energy demand forecasting. By capturing nonlinear relationships between operational variables and electricity demand, the model further supports scenario-based analysis of how different policy environments could influence electrification outcomes.

3.2 Scenario Definitions

Based on information as published by PSA Corporation Limited (previously known as Port of Singapore Authority before 1997)[1], Singapore has deployed 8 electric prime movers and converted more than 60 per cent of port cranes to electric or hybrid variants as of 2024. Based on our estimation from the sustainability report of PSA and other sources, we assumed an overall electrification rate of 60 per cent in the base year 2025. The forecasting horizon is from 2026 to 2035 with electrification rate increasing from 2026 onwards.

Two scenarios are proposed for the purpose of this study, namely, Reference Scenario with 70 per cent electrification rate by 2035 and Fully Electrified Port (FEP) scenario with 100 per cent electrification rate by 2035 (Table 3-1). We further assumed a linear increase from the base year's 60 per cent electrification rate.

Table 3-1 Scenario Setting for the Modelling Analysis

Scenario Definitions	2025	2030	2035
Reference Scenario	60%	65%	70%
FEP Scenario	60%	80%	100%

We would like to highlight that these scenarios should not be interpreted purely as technological pathways, but as outcomes contingent on different levels of policy ambition and demand creation. The FEP Scenario implicitly assumes strong regulatory support, including mandatory electrification measures and carbon pricing mechanisms, which enable accelerated adoption.

In addition, the throughput of Singapore ports is expected to increase from 45 million tonnes in 2025 to 64 million TEUs by 2035 based on estimation from Tuas Port expected capacity of 65 million TEUs by 2040[2], approximately 64 million by 2035 (Figure 3-2).

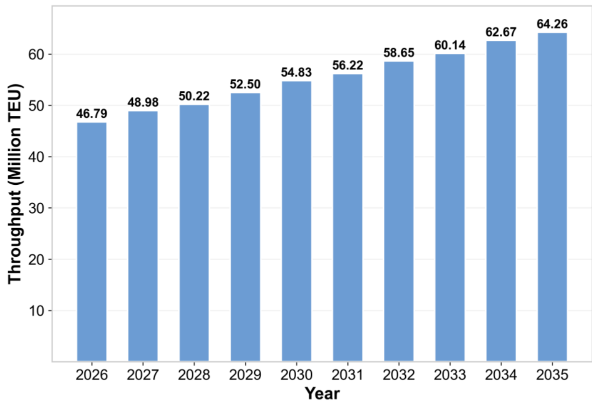

Figure 3-2 Assumed Annual Throughput in Million TEUs

3.3 Data and Assumptions

[1] PSA Singapore. 2025. "PSA Annual and Sustainability Report 2024."

[2] Loi, Esther. 2024. "Singapore's Port Handles Record of over 40 Million Shipping Containers in 2024." The Straits Times, December 27, 2024.

3.3.1 Hourly Ship Berthing Data

The hourly ship berthing data include key vessel and operational information, such as arrival time, vessel type, gross tonnage, vessel length, number of TEUs (acronym for twenty-foot equivalent units) handled, port equipment operation time, and departure time, as shown in Table 3-2. These variables provide a detailed description of the temporal and operational characteristics of vessels during their stay at the port. Among them, arrival and departure times determine the berthing period of each vessel, while vessel type, gross tonnage, length, and TEU capacity reflect differences in vessel size and cargo handling demand. Operation time further characterises the duration and intensity of loading and unloading activities.

Table 3-2 Hourly Ship Berthing Data

A	B	C	D	E	F	G	H	I	J	K
Berthing Time	Vessel Name	Vessel Type	Three-tier Vessel Classification	Length	GT	TEU	Destination Port	Berth at Port of Destination	Operating Duration	Actual Time of Departure
2025/1/1 0:39	COSCO DURBAN	Container	3000-5999TEU	261.1	40447	4253	SINGAPORE	Pasir Panjang Terminal_P34	17.97	2025/1/1 18:37
2025/1/1 1:08	YM INCREMENT	Container	<2999TEU	172.7	16488	1799	SINGAPORE	Brani Terminal_B4	22.38	2025/1/1 23:31
2025/1/1 1:13	OOCL FRANCE	Container	12000-14999TEU	366.5	141003	13208	SINGAPORE	Pasir Panjang Terminal_P41	28	2025/1/2 5:13
2025/1/1 1:57	ONE RELIABILITY	Container	6000-7999TEU	272	74063	7000	SINGAPORE	Pasir Panjang Terminal_P20	29.16	2025/1/2 7:06
2025/1/1 2:46	INCEDA	Container	<2999TEU	172	19035	1774	SINGAPORE	Pasir Panjang Terminal_P31	22.41	2025/1/2 1:10
2025/1/1 2:55	PSA AGILITY	Container	<2999TEU	129.8	7869	841	SINGAPORE	Pasir Panjang Terminal_P04	18.88	2025/1/1 21:47
2025/1/1 2:56	PSA SUSTAINABILITY	Container	<2999TEU	188.5	19131	1716	SINGAPORE	Terminal (Phase 1)_North Quay (	31.01	2025/1/2 9:56
2025/1/1 3:58	MTT BINTANGOR	Container	<2999TEU	171.9	19829	1836	SINGAPORE	Brani Terminal_B7	11.92	2025/1/1 15:54
2025/1/1 4:13	TASMAN	Container	3000-5999TEU	278	66526	5936	SINGAPORE	Pasir Panjang Terminal_P25	11.62	2025/1/1 15:50
2025/1/1 5:33	SAN LORENZO	Container	<2999TEU	276	66046	1708	SINGAPORE	Pasir Panjang Terminal_P32	23.09	2025/1/2 4:39
2025/1/1 5:40	SAWASDEE CHITTAGONG	Container	<2999TEU	172.1	18051	1809	SINGAPORE	Brani Terminal_B5	16.69	2025/1/1 22:21
2025/1/1 5:49	HELGOLAND	Container	<2999TEU	172	18680	1781	SINGAPORE	Pasir Panjang Terminal_P02	20.53	2025/1/2 2:21
2025/1/1 6:01	KOTA SEJARAH	Container	3000-5999TEU	228	41706	3889	SINGAPORE	Brani Terminal_B7	16.11	2025/1/1 22:08
2025/1/1 7:03	EVER EAGLE	Container	6000-7999TEU	300	76067	6332	SINGAPORE	Pasir Panjang Terminal_P29	16.94	2025/1/2 0:00

To support electricity demand forecasting, these vessel-level data are aggregated and converted into hourly time series features, enabling the influence of berthing and handling activities on port electricity demand to be quantified on an hourly basis. The processed hourly berthing data subsequently serve as important input variables for modelling the electricity consumption of port equipment, including shore power systems, quay cranes, yard cranes, and AGVs.

3.3.2 Shore Power Demand

The core issue in the development of shore power infrastructure lies in the power consumption and demand of vessels. Differences in vessel types and port operating modes lead to significant variation in power demand, creating uncertainty and complexity in the planning and demonstration of shore power projects. A clear understanding of vessel energy and power requirements is therefore essential for estimating the electricity consumption of shore power infrastructure.

Different vessel types have varying requirements for shore power in terms of power rating and energy consumption, depending on several key parameters such as vessel size, onboard equipment, container type, and operational profile.

The shore power data for container vessels of different sizes, as published by the IMO, are presented in Table 3-3.

Table 3-3 Shore Power Demand by Container Ships by Size (Unit: kW)

Size (TEU)	Low	Average	High
0-999	0	209	450
1,000-1,999	0	437	910
2,000-2,999	0	395	910
3,000-,4,999	0	625	1350
5,000-7,999	0	640	1400
8,000-11,999	0	710	1600

12,000-14,499	0	800	1800
14,500-19,999	0	865	1950
20,000+	0	865	1950

Energy demand due to shore power connection can be computed by following equation:

$$E_{SP} = P_{ship} * T \quad \text{Eq. 1}$$

where

E_{sp}: Shore power energy consumption, measured in kilowatt-hours (kWh).

P_{ship}: Average power of the ship during berthing, measured in kilowatts (kW).

T: Berthing time, measured in hours (h).

3.3.3 Quay Crane

Based on information in the 2021-updated standards published by Shanghai Municipal Administration for Market Regulation, [3] particularly power rating data for different types of quay cranes are shown in Table 3-4.

Table 3-4 Data for Different Types of Quay Cranes[3]

Type	Rated Load (t)	Lifting Height (m)	Trolley Travel (m)	Test Lifting Travel (m)	Test Trolley Travel (m)	Power Rating Limit (kW/TEU)
Single hoist	35	30	88.5–82.5	20	40	4.19
Single hoist	40	20–29	49–63	15	35	4.57
Single hoist	50	33–36	95–100	25	50	7.39
Single hoist	60–61	36–43	101–110.5	28	60	9.72
Single hoist	65	40–60	110–125	30	60	11.98
Double hoist	65/41	43	110–120	30	60	11.16
Double hoist	115	49	125	30	60	11.18

The mainstream models produced by major manufacturers, such as Shanghai Zhenhua Heavy Industries and Sany Heavy Industry are predominantly 65 tonne single-hoist quay cranes. In recent years, major hub ports, including the Port of Singapore, Shanghai Yangshan Port, and Malaysia's Port of Tanjung Pelepas (PTP), have primarily procured quay cranes of this specification.

Compared with double-hoist quay cranes, 65 tonne single-hoist quay cranes can achieve a good balance between operational efficiency (including the capability to handle twin 40-foot containers), equipment cost, and energy consumption, making them the preferred choice for modern ports, particularly those undergoing electrification retrofitting.

The exact quay crane portfolio is not publicly available in Singapore. As such, this study assumes the median value of 11.98 (kW/TEU) based on the power rating limit of 65 tonne single-hoist quay cranes as the average power demand for quay cranes.

Quay crane energy demand can be computed as

[3] Shanghai Standard. 2021. "Energy Consumption Index and Calculation Method of Quayside Container Crane." DB31/T 781-2021. Shanghai Municipal Administration for Market Regulation.

$$E_{QC} = 11.98KW * h/TEU * TEU \quad \text{Eq. 2}$$

where
E_{QC}: Quay crane energy consumption, measured in kilowatt-hours (kWh).
TEU: Number of TEU loaded and unloaded during the berthing period of each container ship.

3.3.4 Automated Guided Vehicles (AGV)

Based on a study by Stoter et al.[4], the average energy consumption of AGVs 9.35kWh per kilometre travelled when loaded with a container. Based on the average travel distance, the energy consumption for AGVs is estimated to be 9 kW per container move per hour of berthing. Furthermore, based on average AGV travel time, each AGV can move approximately 15 TEUs per hour.

AGV Consumption can be computed as

$$E_{AGV} = 9KW * TEU * T \quad \text{Eq. 3}$$

where
E_{AGV}: AGV energy consumption in kWh.
TEU: Number of TEUs loaded and unloaded during the berthing period of each container ship.
T: Berthing time in hours (h).

3.3.5 Yard Crane

According to Stoter et al.[4], energy consumption by yard crane for moving one TEU is approximately 2 kWh.

The hourly yard crane energy demand can be computed as

$$E_{YC} = 2kWh * TEU \quad \text{Eq. 4}$$

where
E_{YC}: Yard crane energy consumption in kWh.
TEU: The number of TEUs loaded and unloaded during the berthing period of each container ship.

3.3.6 Other Assumptions

The grid emission factor (GEF) value for Singapore is assumed to maintain around 0.402 kg-CO_2/kWh based on published value from the Energy Market Authority of Singapore. Emission factors of diesel is assumed to be 2.68 kg-CO2/L, 0.001 kg-SOx/L, 0.042 kg-NOx/L, and 0.0015 kg-PM/L respectively based on the fuel emission factor values published by the Intergovernmental Panel on Climate Change U.S. EPA and European Environment Agency's standards for heavy-duty machinery, and the National Environment Agency of Singapore's standards for ultra-low sulphur diesel.

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[4] Stoter, Jasper, Xinyu Tang, Milos Cvetkovic, Peter Palensky, Henk Polinder, Çağatay Iris, and Frederik Schulte. 2025. "Energy Management and Stochastic Operations Planning for Electrified Container Terminals with Uncertain Energy Supply and Demand." Journal of Cleaner Production 527 (September):146383.

Based on our historical data survey, diesel price is assumed to remain around 2025 average level at about 2 SGD/L and electricity price is set at 25 cents/kWh, based on the regulated tariff for commercial and industrial customers in 2025 in Singapore. For diesel used in ship auxiliary engine for onboard electricity generation, the price is assumed to be 1.6 SGD/L based on the average Asian diesel price in 2025.

When estimating the additional investments due to electrification, we further assumed the following unit investment values:

- S$0.65 million/MW for the power grid[5]
- S$1.05 million/MW for quay cranes and S$1.00 million/MW for yard cranes[6]
- S$2.75 million/MW for Shore Power[7].
- S$1.25 million/MW for AGV and charging infrastructure[8].

The modelling assumptions, particularly those related to fuel prices, carbon pricing, and grid emission factors, should be understood as reference conditions based on our understanding of publicly available information. In practice, policy-driven changes, such as rising carbon prices and declining grid emission intensity could significantly alter the results.

4 Model Performance Evaluation

4.1 Validation

Model validations are performed on both Singapore and Shanghai Ports to establish confidence for the basis of estimation. Electricity consumptions by Singapore Ports are estimated based on the annual Scope 2 emissions of as disclosed in PSA's Sustainability Reports for 2022, 2023 and 2024 as well as the grid emission factor as released by Singapore's Energy Market Authority (EMA) (Table 4-1).

Electricity consumption can be computed as

$$E = GHG2/GEF \qquad \textit{Eq. 5}$$

where

E: annual electricity consumption (GWh).

GHG2: annual Scope 2 GHG emissions (kt-CO_2e).

GEF: grid carbon emission factor (kg-CO_2/kWh).

Table 4-1 Estimated Electricity Consumptions by Singapore Ports 2022-2024

Estimation for PSA Ports	2022	2023	2024
Grid Emission Factor (kg-CO_2e/KWh)	0.407	0.412	0.402
Scope 2 GHG Emissions (kt-CO_2e)	149	130	157
Estimated Electricity Consumption（GWh)	366	315	390

[5] SP PowerAssets Limited. 2025. "Transmission Service Rate Schedule."

[6] Port Equipment Manufacturers Association. 2013. "Electrification of RTG Cranes in Ports and Terminals."

[7] Maritime and Port Authority of Singapore. 2022. Maritime Singapore Decarbonisation Blueprint: Working towards 2050.

[8] ABB. 2020. "Smart Charging Infrastructure for Singapore Port's Automated Guided Vehicles | ABB." Case Study. June 25, 2020. https://new.abb.com/news/detail/63868/smart-charging-infrastructure-for-singapore-ports-automated-guided-vehicles.

The same approach is used to estimate the electricity consumption of Shanghai Ports which is based on the sustainability reports published by Shanghai International Port Group (SIPG)[9] and the annual GEF values published by Shanghai Municipal Ecology and Environment Bureau, & Shanghai Municipal Bureau of Statistics[10] [10]. Among all Shanghai Ports, Yangshan Port is the most comparable to Singapore Ports and hence is used in this study. Based on historical data, Yangshan Port accounts for about 55 per cent the total electricity consumptions of all Shanghai Ports (details shown in Table 4-2). In comparison, our model estimates that the 2025 energy consumption of Shanghai Port and Yangshan Port will be approximately 520 GWh and 290 GWh, respectively, representing differences of only about 7 per cent and 6 per cent from the officially reported data, which can be considered negligible. The modelled share of Yangshan Port relative to the total for Shanghai Port is around 45 per cent, closely aligned with the 44 per cent derived from official data. This demonstrates that the modelling framework is able to produce reasonably accurate predictions that are consistent with reported figures.

Table 4-2 Electricity Consumptions in Yangshan Port 2022-2025

Estimation for Shanghai Ports	2022	2023	2024	2025
Grid Emission Factor (kg-CO_2e/KWh)	0.485	0.478	0.470	0.470
Scope 2 GHG Emissions (kt-CO_2e)	186	200	217	265
Energy Demand Prediction in Shanghai Port (GWh)	383	418	461	563
Energy Demand Prediction in Yangshan Port (GWh)	211	230	254	309

4.2 Accuracy in Pattern Prediction

The key indicator for evaluating model performance is the coefficient of determination, R^2, complemented by visual comparison between predicted and historical data patterns. Figure 4-1 presents the performance evaluation results of the energy consumption prediction model for the Port of Singapore in 2025. The model demonstrates very high fitting accuracy and generalisation capability on both the training set (hourly data from January to October 2025) and the test set (November-December 2025), with a coefficient of determination of $R^2 = 0.9732$, indicating that the model explains 97.32 per cent of the variance in energy consumption.

However, it is important to emphasise that high predictive accuracy does not necessarily translate into how real-world deployment will or should unfold. There will always be uncertainties that cannot be fully captured in modelling analysis. External factors such as policy changes, market behaviour, and the evolution of the energy system will inevitably shape actual outcomes.

In terms of curve morphology, the model predictions (light orange and pink curves) closely align with the actual energy consumption values (light blue and dark blue curves) for both the historical data in the training phase and the new data in the test phase. Even at peak energy consumption levels (approaching 300,000 kW), the model accurately captures the trends without significant deviation.

Further analysis of the time series characteristics of the energy consumption data shows that port energy consumption exhibits significant periodic fluctuations, which are strongly

9 Shanghai International Port (Group) Co. Ltd. 2025. "SPIG Sustainable Development Report 2024."

10 Shanghai Municipal Ecology and Environment Bureau and Shanghai Municipal Bureau of Statistics. 2026. "Carbon Dioxide Emission Factors of Electricity and Heat for Shanghai Public Power Grid (2020-2024)."

correlated with the 24-hour operating rhythms, shift schedules, and vessel arrival patterns. Energy consumption approaches 0 kW at troughs and can reach nearly 300,000 kW at peaks, reflecting a wide amplitude and substantial variation in port operational intensity. The energy consumption patterns, peak ranges, and fluctuation frequencies are highly consistent between the training and test sets, indicating that the patterns learned by the model are generalisable and not the result of overfitting to data from a specific month.

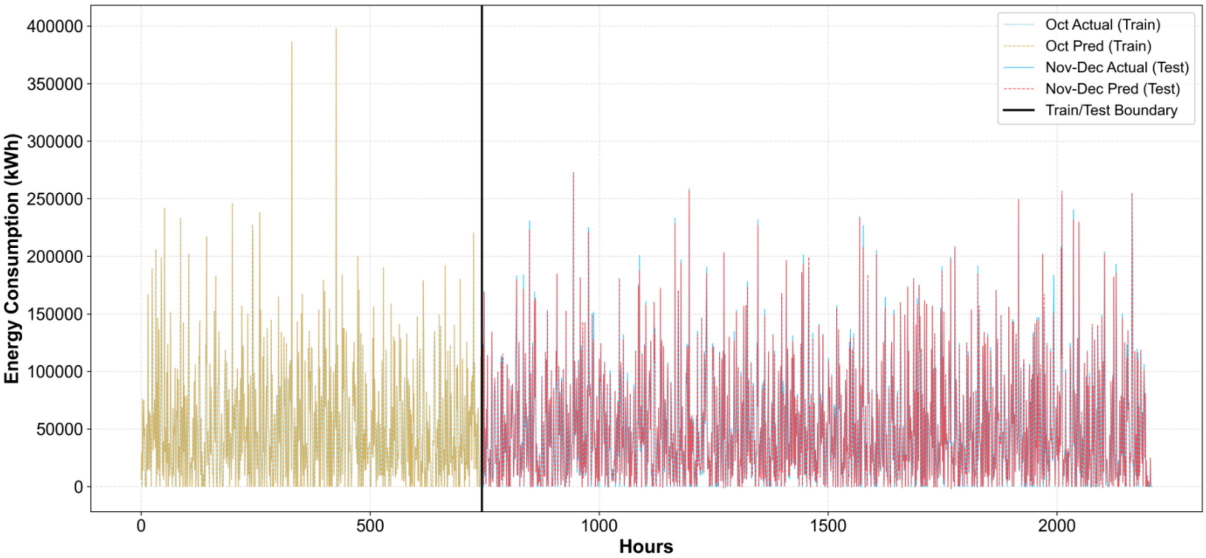


Figure 4-1 Singapore Port Energy Prediction Analysis of 2025 (R^2 = 0.9732)

The same modelling approach is further tested using data from Yangshan Port. Using energy consumption data from Yangshan Port for the period January to October 2025 for training, the model is used to predict energy consumption for November and December. Same as the findings from those of Singapore Port, the predicted values show strong agreement with the actual values, thereby demonstrating the model's reliability and accuracy as shown in Figure 4-2. Yangshan Port is considered comparable to Singapore due to its similar role as a large-scale automated container terminal with high electrification levels, making it a suitable benchmark for validation.

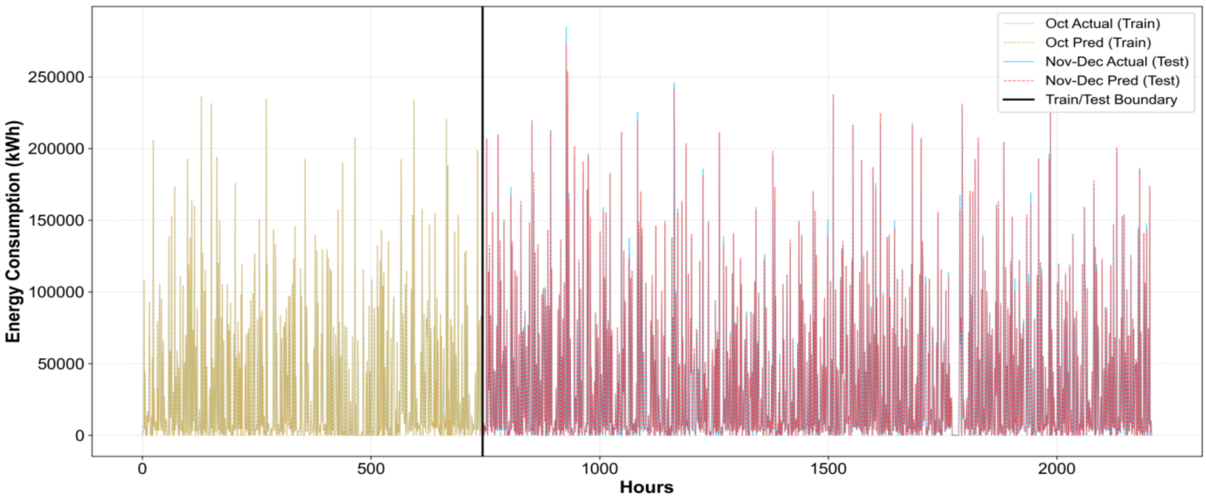


Figure 4-2 Yangshan Port Energy Prediction Analysis of 2025 (R^2 = 0.9718)

In summary, the prediction model not only captures the periodic patterns and peak characteristics of port energy consumption effectively, but also demonstrates strong generalisation capability, thereby providing reliable prediction for the purpose of this study.

5 Modelling Analysis Results

The modelling results as presented in this section assumes normal long-term trajectory in international trade and has not accounted for disruptions such as the Iran War.

5.1 High Resolution Demand Prediction

Based on the hourly historical data on port throughput (measured in TEU), the first step is a high-resolution long-term demand projection measured in TEU based on projected total annual demand as published by MPA (Figure 5-1).

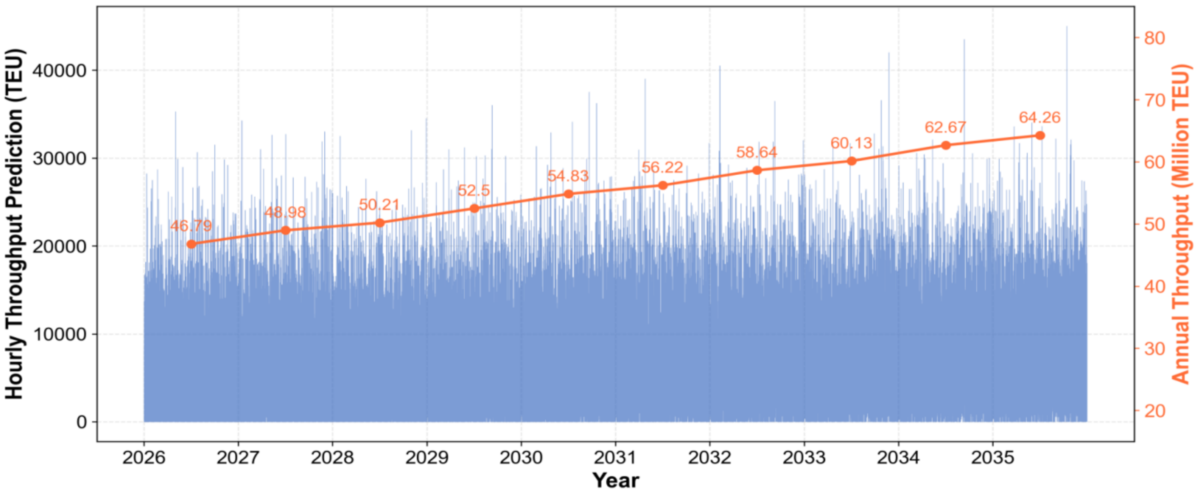


Figure 5-1 Hourly and Annual Throughput (2026-2035 Predicted Values)

This high-resolution demand projection data can then be used to estimate hourly energy demand from 2026 to 2035 (assuming the efficiency of full-electric equipment) as shown in Figure 5-2. The demand projections highlight both the fast-rising demand for electricity and potentially rising variations in hourly, daily and seasonal load variability. This further highlights the importance of aligning infrastructure development with policy-driven demand signals to effectively account for the growing annual demand with the observed variability so as to avoid under-utilisation or over-investment. The demand projection data are further used to present annual total energy demand in subsequent sections. The full-electric assumption is further used to decompose into diesel and electricity demand to reflect current technology mix and for future projections.

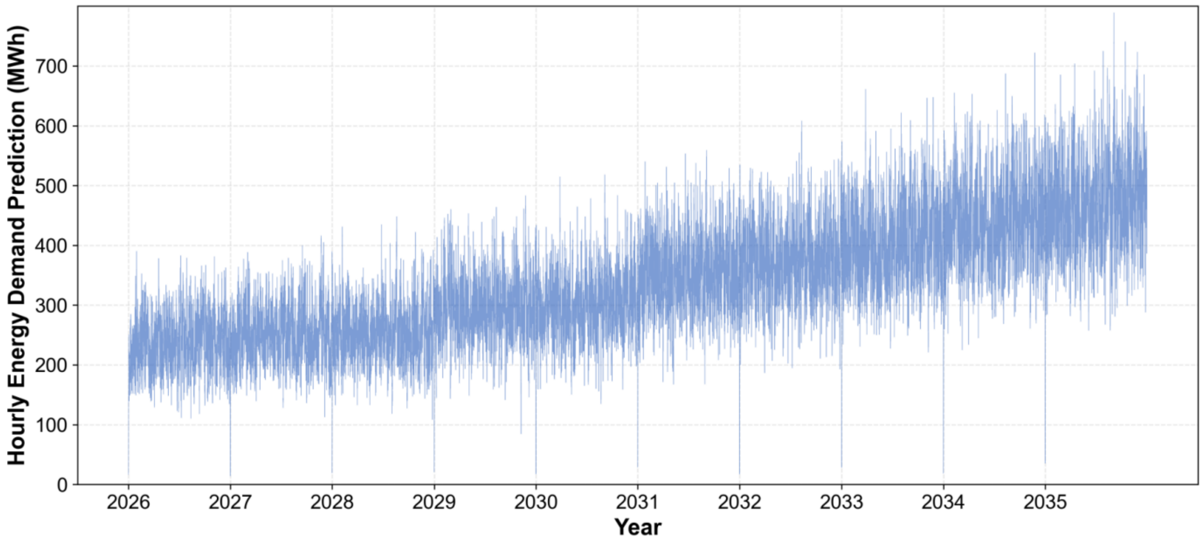


Figure 5-2 Predicted Hourly Port Energy Demand 2026-2035

Despite a 30 per cent difference in electrification rate between the Reference and FEP Scenarios by 2035, the magnitude of peak energy demand growth differs substantially. Under the FEP Scenario, peak demand rises sharply by more than 3.5 times, reaching approximately 789.7 MWh by 2035, reflecting the collective impact of fully electrified equipment and shore power systems during peak operations (Figure 5-3). In contrast, the more gradual pathway (i.e. the Reference Scenario) results in a significantly lower peak of around 473.9 MWh, indicating a more manageable increase in load. This highlights that the pace and extent of electrification are critical determinants of peak demand intensity, with faster and more complete electrification placing disproportionately higher pressure on power infrastructure.

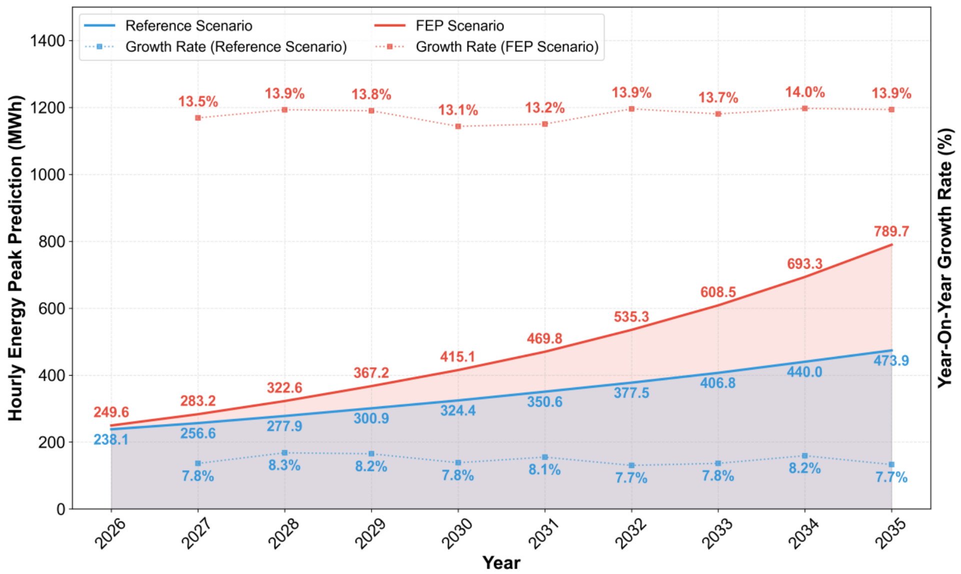


Figure 5-3 Peak Hourly Electricity Demand by Year by Scenario

5.2 Annual Energy Demand Prediction

5.2.1 Total Energy Demand Prediction

Based on the assumed growth trajectory of annual port throughput, the growth in the number of TEUs is expected to be about 37.3 per cent between 2026 and 2035. Based on modelling results, the annual energy demand is expected to increase by about 37.4 per cent from 455 GWh to 625 GWh (based on electric-equivalent energy demand prediction) as shown in Figure 5-4. The close alignment between these growth rates indicates an almost linear positive relationship between throughput and energy demand. Under the current technological and electrification transition context, port energy demand remains strongly coupled with operational scale, with each incremental increase in throughput accompanied by a proportional rise in energy consumption.

It is important to highlight that the increase in energy demand under the Reference Scenario is driven primarily by growth in throughput and, consequently, port operational intensity. In contrast, under the FEP Scenario, the increase is largely driven by regulatory signals and policy incentives aimed at phasing out fossil fuel alternatives by 2035, including the electrification of port equipment and the adoption of shore power.

At the same time, both throughput and energy consumption exhibit a stable and predictable long-term growth trajectory, with no significant fluctuations. This provides a robust basis for subsequent scenario-based analysis in which we decompose the total electric-equivalent demand based on fuel, namely, electricity and diesel.

However, by 2035, total port energy consumption is projected to exceed 600 GWh. In the context of continued expansion, this will place increasing pressure on conventional energy supply and associated carbon emissions. These trends underscore the urgency of accelerating the transition towards full electrification and increasing the share of renewable energy. However, we also note the importance of zero or near zero emission fuels such as low-carbon ammonia and hydrogen as part of the broader maritime decarbonisation strategy

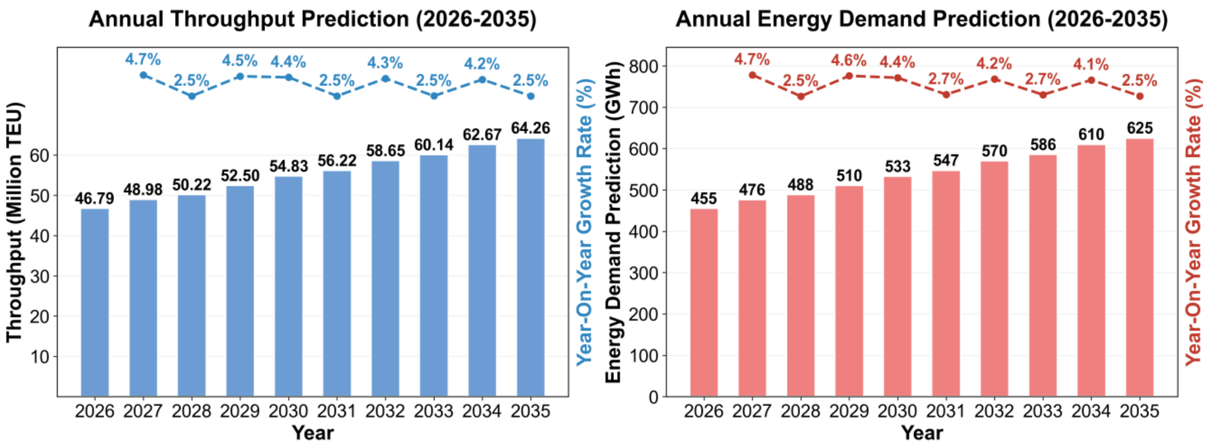


Figure 5-4 Predicted Annual Energy Demand 2026 -2035

5.2.2 Energy Demand Prediction by Equipment

Figure 5-5 shows the evolution of total energy demand and its composition across major equipment categories from 2026 to 2035 with the assumption that electrification will occur simultaneously for onshore equipment and OPS adoption in proportion due to strengthened policy and regulatory effort. In terms of composition, the overall structure remains stable with slight shifts. Yard cranes consistently account for the largest share, increasing slightly to around 65 per cent by 2035, highlighting their central role in yard operations. AGVs maintain a share of approximately 15 to 20 per cent. Shore power is expected to increase to about 48.12 GWh by 2035 assuming all container vessels berthing at Singapore ports will connect to shore power. Overall, we can observe two key dynamics from Figure 5-5. First, energy demand grows in tandem with both operational scale and electrification (as reflected in the preceding section). Next, core equipment such as yard cranes and AGVs represent the primary levers for decarbonisation. These findings suggest that targeted electrification of key port equipment, such as yard cranes and AGVs can deliver the most significant emissions reductions.

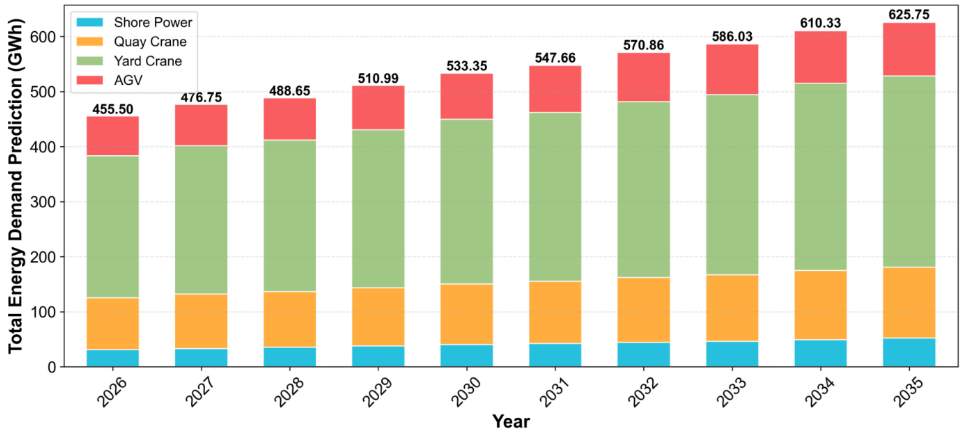


Figure 5-5 Predicted Annual Energy Demand by Equipment

As of this step, all energy demand values are modelled by assuming the use of full-electric equipment. This establishes a basis on the estimated ‘energy service demand’ which will be further decomposed to allow a fraction of such ‘services’ to be met by diesel-powered equipment, including both cranes and AGVs.

5.2.3 Decomposing Fuel Use by Type

In this step, ‘services’ to be supplied by diesel-powered equipment are calculated based on current and assumed future electrification rate as well as the efficiency difference between diesel-power equipment and full electric-equipment.

The calculation steps follow Equations 6 to 8:

$$E_{elc\_eqpt} = E_{annual} \times \alpha \quad \text{Eq. 6}$$

$$E_{dsl\_service} = E_{annual} \times (1 - \alpha) \quad \text{Eq. 7}$$

$$E_{dsl\_eqpt} = E_{dsl\_service} \times \delta \quad \text{Eq. 8}$$

where

E_{elc_eqpt}: Electricity consumption (GWh) considering electrification percentage.

E_{annual}: Modelled annual electricity consumption (GWh) assuming fully electrified.

α: Electrification percentage of the corresponding year.

$E_{dsl\_service}$: Energy service (represented by electric-powered equipment to be supplied by diesel-powered equipment (GWh).

δ: Efficiency between diesel engine and electric motor (diesel internal combustion engine is typically 3.33 times less efficient than electric-powered systems)
E_{dsl_eqpt}: Energy demand by diesel-powered equipment (GWh)

The resulting fuel demand prediction by type is presented in Figure 5-6. In the Reference Scenario, diesel demand continues to increase albeit a slower pace as compared to a situation in which electrification stays constant at the current level of 60 per cent. Diesel remains a significant contributor to port emissions over the outlook period 2025-2035. In the FEP Scenario, the aggressive diesel phase-out is designed to align with regulatory and economic drivers such as carbon pricing and mandatory OPS adoption, demonstrating how policy signals directly translate into predictable demand for low-carbon solutions. While the absolute reduction percentage is rapidly increasing right after 2026, the rate of increase in diesel phase-out is relatively mild till 2032 at 1 to 4 percentage points, and is quickly accelerated to 10, 16 and 52 percentage points in the final three years of the outlook period.

In the FEP Scenario (as compared to the Reference Scenario), the amount of diesel displaced by electrification is equivalent to removing about 7,200 diesel heavy trucks by 2035, almost 50 per cent of the total heavy goods vehicles (incl. trailers) in Singapore. This further demonstrates the importance of policy and regulatory push in driving fossil-fuel phase out and emission reductions.

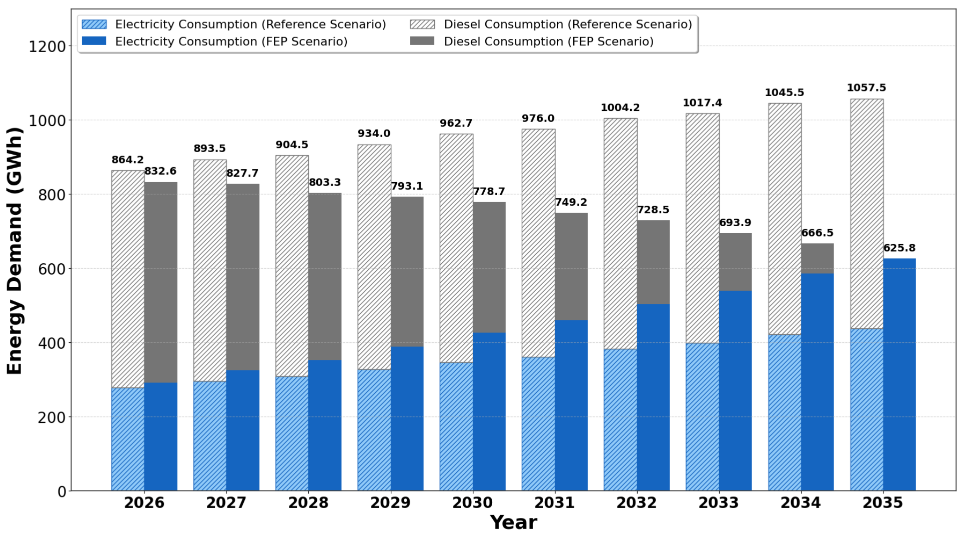


Figure 5-6 Predicted Energy Demand by Fuel Types by Scenario

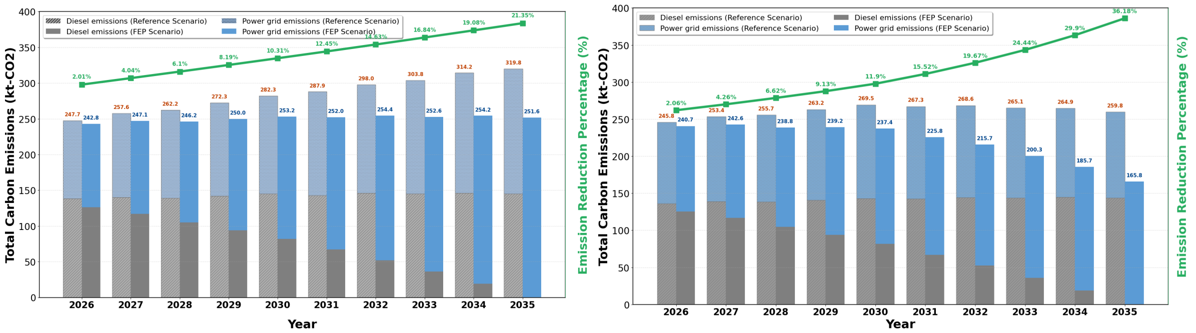
6 Environmental Benefits of Electrification

The total environmental benefits of electrification are evaluated based on reductions in CO_2 and air pollutants (i.e. SOx, NO_x, and PM). The environmental emissions are calculated based on the assumed GEF values of Singapore's power grid and diesel emission factors as explained in the "other assumptions" earlier on. The total emissions are presented based on port equipment and shore power. While electrification can lead to direct emissions reductions, it should be considered as part of a broader energy system transition in which emission reduction outcomes are influenced by both fuel switching and the carbon intensity of electricity supply (i.e. the grid emission factor).

6.1 Phase-Down/Out of Diesel-Powered Port Equipment

The annual carbon emission and air pollutant reductions are modelled in the FEP Scenario are further divided based on two assumptions, namely, a constant GEF post 2025 and a reducing GEF based on data published by the EMA[11]. In both cases, the FEP Scenario will completely eliminate the use of fossil fuel by 2035.

Assuming a constant GEF post-2025, electrification could achieve 21.4 per cent annual carbon emission reductions or 68 kt-CO_2 for port equipment by 2035, as the steep decline in diesel emissions significantly offsets the increase in carbon emissions due to shifting demand to the power grid (Figure 6-1a). The amount of reduction is equivalent to approx. 37,800 units of 4-room HDB flats' annual emissions.



(a) Constant GEF *(b) Declining GEF*

Figure 6-1 Carbon Emissions by Scenario – Port Equipment

Based on data published by the EMA, we further incorporate a scenario in which the GEF declines annually, decreasing from 0.402 to 0.265 kg-CO_2/kWh by 2035. Under this scenario, electrification can achieve a 36.2 per cent reduction in annual carbon emissions or 94 kt-CO_2 by 2035 (Figure 6-1b). The reduction amount is equivalent to approx. 52,200 units of 4-room HDB flats' annual emissions This indicates that a declining GEF can significantly amplify the overall emissions reduction potential.

This represents a direct and unambiguous decarbonisation benefit, as emissions from diesel combustion are permanently removed rather than shifted across sectors. In the absence of viable alternative low-carbon fuel, electrification might be the only feasible pathway to eliminate the use of fossil fuel or Scope 1 emissions.

In terms of air pollutants, the FEP Scenario can lead to a cumulative reduction of 11,269.97 tonnes of NO_x, 268.33 tonnes of SO_x and 402.50 tonnes of PM by 2035 (Figure 6-2).

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[11] Energy Market Authority of Singapore. 2022. "Energy 2050 Committee Report."

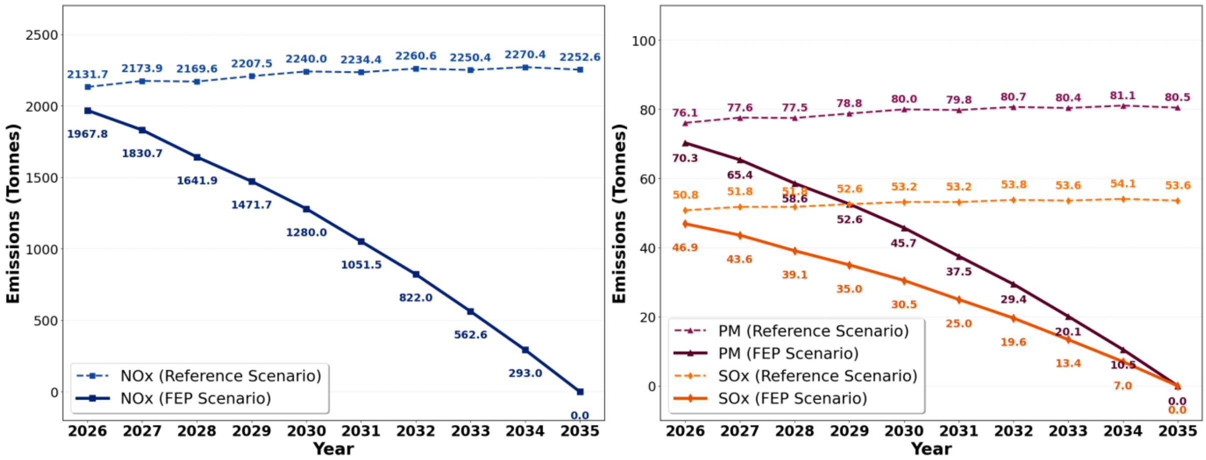
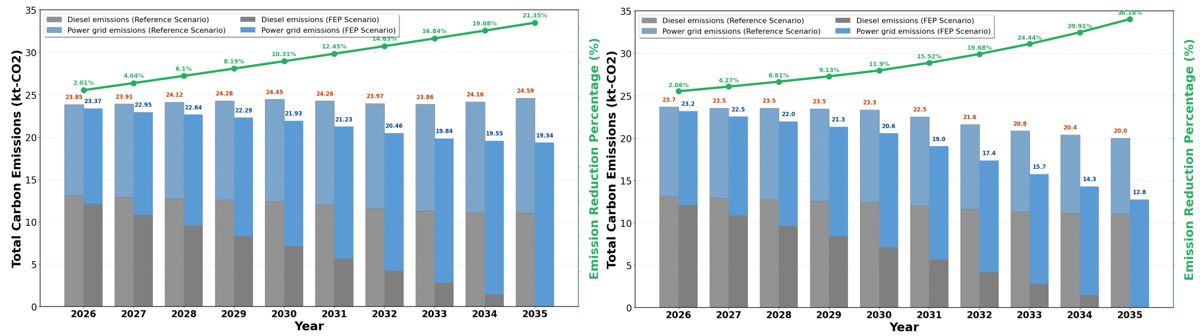


Figure 6-2 Air Pollutant Emissions by Scenario – Port Equipment

6.2 Shore Power

The modelling analysis of emission reductions and attributions due to shore power adoption are calculated under the current international regulation. As such, carbon emissions due to the use of diesel in auxiliary ship engine while berthing are not attributable to Singapore, but the carbon emissions due to the use of shore power are attributable to Singapore. Hence, the use of shore power under the current emission accounting framework will lead to a transfer of carbon emissions from ships to ports, despite a net reduction of the overall carbon emission quantity.

Assuming a constant GEF post-2025, electrification could achieve an emission reduction of 5.2 kt-CO_2 per year by 2035, or the equivalent of 21.4 per cent reduction (Figure 6-3a). Under the current GHG emission accounting framework, shore power effectively transfers GHG emissions from ships to ports. Compared to the Reference Scenario, the FEP Scenario can achieve a 21.35 per cent reduction in annual carbon emissions or 5.2 kt-CO_2 by 2035 (Figure 6-3a). The expected annual transfer of GHG emissions will increase from 0.53 kt-CO_2 per year in 2026 to 6 kt-CO_2 per year by 2035, with a cumulative transfer of 31 kt-CO_2 in the outlook period. In effect, the amount of carbon emission transferred from ships to ports could 'undo' 9 per cent of port electrification decarbonisation gains.



(a) Constant GEF *(b) Declining GEF*

Figure 6-3 Carbon Emissions by Scenario – Shore power

With improvements in grid carbon intensity, the net emissions benefit of shore power will increase significantly. Assuming a declining GEF, the FEP Scenario can achieve a 36.18 per cent reduction in annual carbon emissions or 7.2 kt-CO_2 by 2035 (Figure 6-3b). The expected annual transfer of GHG emissions will increase from 0.52 kt per year in 2026 to 4 kt per year by 2035, with a cumulative transfer of 24 kt in the outlook period. In effect, the amount of carbon emission transferred from ships to ports could ‘undo’ 4 per cent of port electrification decarbonisation gains.

While shore power introduces a shift in emissions accounting, from ships to ports or the national grid, it should not be interpreted as reducing the effectiveness of electrification. **What’s urgently needed is a framework that allows fair and transparent redistribution of emissions across sectors under existing accounting frameworks.** From a system’s perspective, shore power reduces total emissions by replacing less efficient onboard diesel generation with grid-based electricity, particularly as the grid becomes cleaner over time. **Although this might be seen as “undoing” emissions reduction efforts by ports, shore power changes the location of emissions while contributing to overall system efficiency gains and enabling deeper decarbonisation when combined with grid improvements.**

As such, there is an urgent need to establish fair and transparent regulatory attribution and pricing mechanisms that ensure shore power adoption is financially rewarded and aligns with broader zero-emission pathways.

In terms of air pollution reductions, compared with the Reference Scenario, the FEP Scenario can lead to a cumulative reduction of 918.14 tonnes of NO_x, 21.86 tonnes of SO_x and 32.79 tonnes of PM (Figure 6-4).

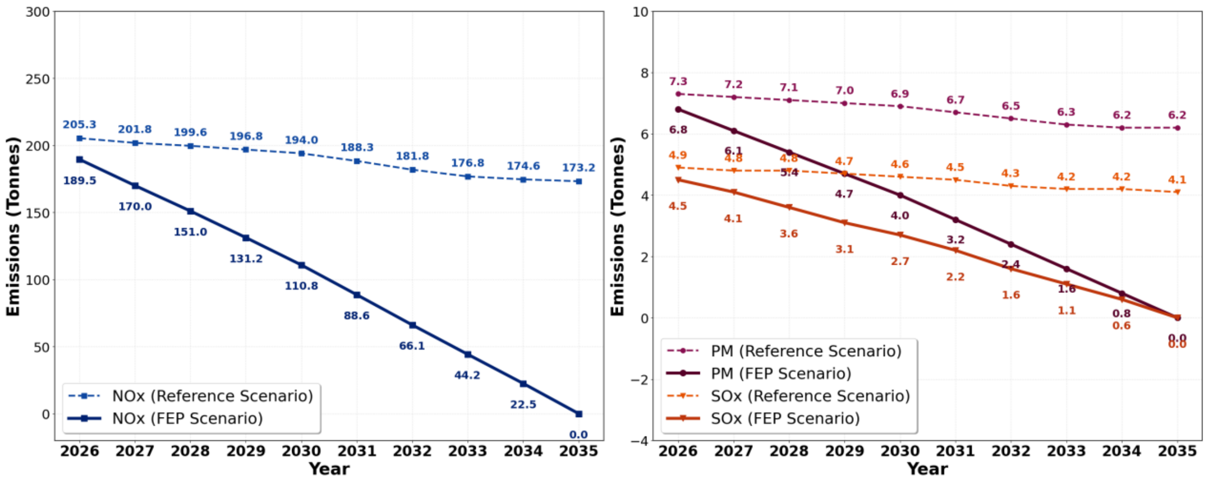


Figure 6-4 Air Pollutant Emissions by Scenario – Shore Power

7 Cost-benefit Analysis

7.1 Fuel Cost Savings

Operating cost savings are computed based on the amount of diesel replaced in the Reference Scenario and FEP Scenario due to electrification. Since diesel prices are usually given based on volume (litre or L in this case), we further converted the computed energy service demand to be met by diesel by an additional 3.5 kWh/L to obtain the diesel demand in volume based on information published in the latest survey by the Port Equipment Manufacturers Association.[12] Based on historical data survey, diesel price is assumed to remain around 2025 average level at about 2 SGD/L and electricity price is set at 25 cents/kWh, based on the regulated tariff for commercial and industrial customers in 2025. Please note that the present study **has not accounted for expected fuel price spiking due to recent geopolitical events, as well as savings in maintenance cost for diesel-powered equipment**.

7.1.1 Port Equipment

Due to efficiency gain from electrification, there is visible fuel cost reductions as shown in Figure 7-1. By 2035, full electrification can achieve an annual fuel cost reduction of more than SGD 30 million with a cumulative cost savings over SGD 191 million between 2026 and 2035.

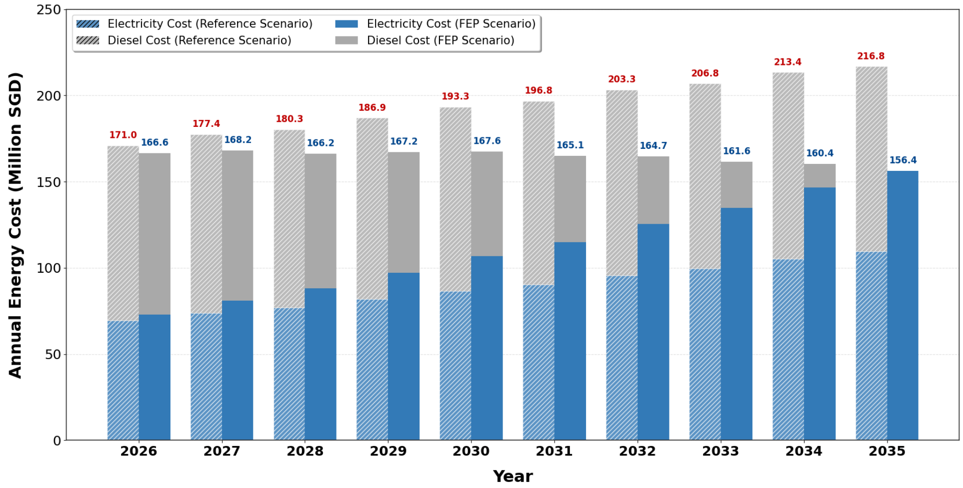


Figure 7-1 Annual Fuel Cost by Scenario – Port Equipment

7.1.2 Shore Power

In the Reference Scenario, there is already cost saving due to mildly increased electrification rate. In comparison, by 2035, the FEP Scenario is projected to achieve a cumulative operating cost reduction of S$12 million compared to Reference Scenario (Figure 7-2) for ship owners/operators, based on current fuel price assumptions. For ports, shore power could lead to potential cumulative revenue of 12.23 million between 2026 and 2035.

[12] Port Equipment Manufacturers Association (PEMA). 2025. "Global Survey of Mobile Equipment Deliveries 2024."

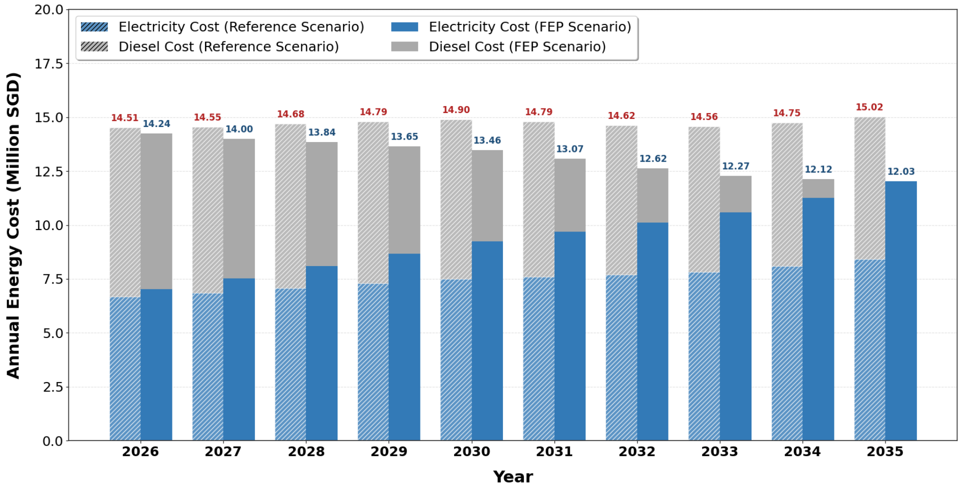


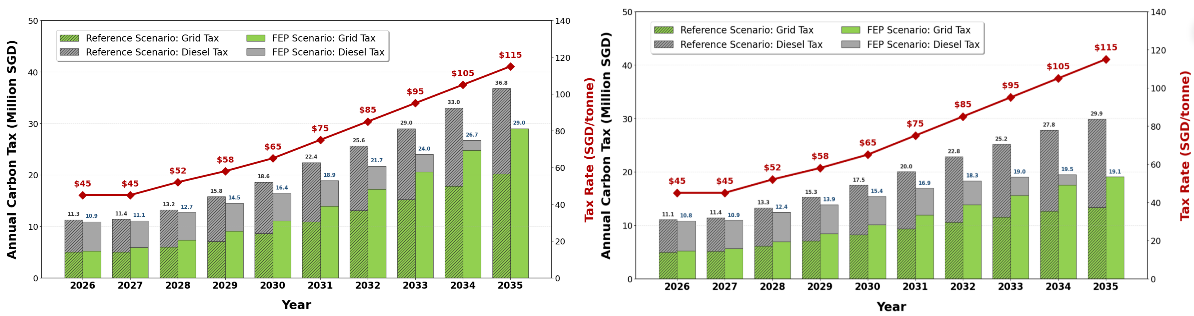
Figure 7-2 Annual Fuel Cost by Scenario – Shore Power

7.2 Carbon Tax Savings

To align with Singapore’s "Net Zero by 2050" ambition, the fiscal impact of carbon emissions is evaluated based on the carbon tax trajectory as announced in Budget 2022. The policy stipulates a progressive increase in the carbon tax rate: S$25/t for 2024–2025, S$45/t for 2026-2027, and S$50 - S$80/t by 2030 and beyond. As such, we assume that carbon tax could rise to about $115/t by 2035 as Singapore further tightens emission control towards its net-zero goals.

7.2.1 Savings from Port Electrification

Under constant GEF scenario, the cumulative carbon tax payment is approximately S$143 million and S$125 million in the Reference and FEP Scenarios respectively, demonstrating a potential savings of S$18 million. Under declining GEF scenario, the cumulative carbon tax payment is approximately S$131 million and S$108 million in the Reference and FEP Scenarios respectively, demonstrating a potential savings of S$23 million. Figure 7-3 shows the estimated amount of carbon tax payment annually between 2026 and 2035 based on projected carbon prices and assuming all carbon emissions are liable for carbon tax payment. With a higher carbon tax rate in the future, savings in carbon tax is expected to be greater.



(a) Constant GEF *(b) Declining GEF*

Figure 7-3 Carbon Tax Payment – Port Operation

7.2.2 Savings and Transfers due to Shore Power

The shore power carbon savings are calculated based on a couple of strong assumptions. We note that such assumptions do not reflect the current policy and regulatory framework in

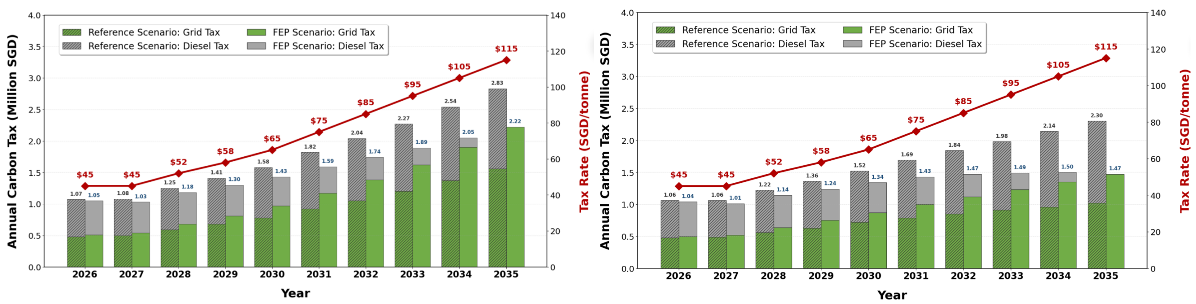
Singapore or internationally on carbon tax, but our findings could be used as a starting point to rethink carbon tax as well as emission inventory attribution in Singapore, regionally and globally.

Assuming carbon is taxable for both shore power and diesel usage while berthing, Figure 7-4 shows the estimated amount of carbon tax payment annually from 2026 to 2035 based on projected carbon prices and assuming all carbon emissions are liable for carbon tax payment. Under the constant GEF scenario, the FEP Scenario is expected to achieve a collective carbon tax reduction of S$1.5 million over the same period relative to the Reference Scenario for both ships and ports, while it is S$1.8 million under the declining GEF scenario.

Under the constant GEF scenario, the Reference Scenario is already expected to see shore power–related carbon tax increase annually from S$0.48 million in 2026 to S$1.56 million by 2035, resulting in a cumulative transfer of S$6.1 million from ships to ports over the period. In comparison, under the FEP Scenario, shore power–related carbon tax rises from S$0.51 million in 2026 to S$2.22 million by 2035, with a cumulative transfer of S$7.7 million between 2026 and 2035.

Under the declining GEF scenario, the Reference Scenario is expected to see shore power–related carbon tax increase annually from S$0.48 million in 2026 to S$1.03 million by 2035, resulting in a cumulative transfer of S$5.1 million from ships to ports over the period. In comparison, under the FEP Scenario, shore power–related carbon tax rises from S$0.5 million in 2026 to S$1.47 million by 2035, with a cumulative transfer of S$6.3 million between 2026 and 2035.

The increased carbon tax burden is concerning, as electrification shifts emissions to the power sector, making costs dependent on grid carbon intensity. If the grid remains carbon-intensive, higher electricity use can increase indirect emissions and tax liabilities. This may weaken the short-term economic case, highlighting the need for well-designed carbon pricing and supportive policies. The increasing carbon price trajectory plays a critical role in strengthening the economic case for electrification. Without carbon pricing, the financial attractiveness of electrification would be significantly weaker.



(a) Constant GEF *(b) Declining GEF*

Figure 7-4 Carbon Tax Payment – Shore Power

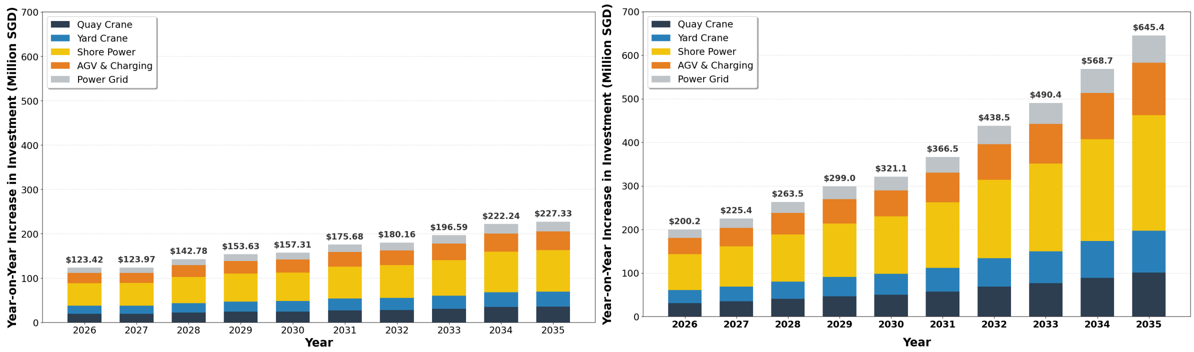
7.3 Future Investment Needs

Future investment needs are estimated based on approaches, namely, peak power demand and total consumption.

7.3.1 Capacity Expansion Based on Peak Power Demand

Based on the assumed unit investment cost as explained in the "other assumptions" section, (a) Constant GEF (b) Declining GEF

Figure 7-5 presents the estimated year-on-year incremental investment for grid infrastructure expansion and port equipment in the Reference Scenario and the FEP Scenario based on Peak Power demand.



(a) Constant GEF *(b) Declining GEF*

Figure 7-5 Year-on-Year Increase in Capacity Investment based on Peak Power Demand

The Reference Scenario as shown in (a) Constant GEF (b) Declining GEF

Figure 7-5a presents a steady, incremental investment profile with an estimated cumulative investment of S$1.2 billion between 2026 and 2035. This comprises S$114.45 million for power grid related infrastructure expansion, S$184.89 million for quay cranes, S$176.08 million for yard cranes, S$484.23 million for OPS, and S$220.11 million for AGV charging infrastructure.

The FEP Scenario as shown in (a) Constant GEF (b) Declining GEF

Figure 7-5b presents an aggressive investment trajectory, with annual incremental investment near-tripling by 2035. The total cumulative investment between 2026 and 2035 is estimated to be about S$2.6 billion. This includes S$247.41 million for power grid related infrastructure expansion, S$399.66 million for quay crane, S$380.63 million for yard crane, S$1,046.72 million for OPS, and S$475.78 million for AGV charging infrastructure.

For port equipment, the total incremental investment from 2026 to 2035 (between FEP and Reference Scenarios) is S$741.46 million. Under the constant GEF scenario, the total savings (combining fuel cost savings and carbon tax savings) is approximately S$208.71 million between 2026 and 2035. Therefore, a complete payback of the total incremental investment will require another 16 years to 2051. Under the declining GEF scenario, the total cost savings is approximately S$213.1 million, and the total payback can be achieved by 2050.

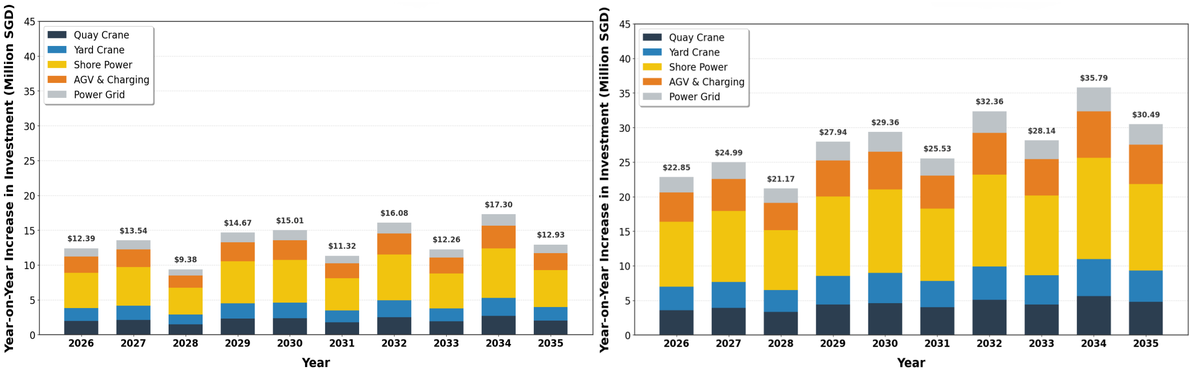
For shore power, without accounting for carbon taxes, the total incremental investment from 2026 to 2035 (between FEP and Reference Scenarios) is S$628.97 million. The total incremental revenue from electricity sales via shore power is approximately S$12.23 million (between FEP and Reference Scenarios). Without accounting for added carbon tax, the total payback period is likely to be 342 years from 2035 regardless of the assumptions on future GEF trajectories.

When carbon tax is added to the calculation, the payback period is likely 411 years from 2035 under the constant GEF scenario, and 445 years under the declining GEF scenario. Although the payback period became longer under the declining GEF scenario, it also implies that the total carbon tax payment is reduced due to a cleaner grid as shown in Section 7.2. To further assure the assumptions and results, we analysed the payback period for the Reference Scenario and found that the payback period even under the Reference Scenario (only 10 per cent increase in electrification by 2035 as compared 2025) would be more than 100 years.

Although the absolute value of the cumulative investments at S$1.2 to 2.6 billion over 10 years is unlikely to represent a significant investment barrier, the expectations on payback between port equipment and shore power might need to be very different. The results from our modelling analysis are entirely due to the assumption on the current fuel and shore power electricity prices. With proper pricing mechanisms and a mandate for the adoption of shore power and carbon, the payback is very likely to be shortened. In addition, we only considered an extreme scenario in which grid infrastructure expansion alone is assumed to accommodate for peak demand. In reality, the use of an energy storage system coupled with renewable energy could also help significantly shorten the payback period. As such, electrification should be framed as a long-term strategic investment that should be managed through careful long-term planning, policy and regulatory mandates, and proper financing (e.g. carbon pricing and green financing) to ensure project bankability.

7.3.2 Capacity Expansion Based on Annual Demand Increase

Capacity expansion based on annual demand increase can be considered a naturally evolving need for infrastructure upgrade. Figure 7-6 presents the estimated year-on-year increase in investment for grid infrastructure expansion and port equipment in the Reference Scenario and the FEP Scenario based on the gradual increase in annual energy demand due to electrification.



(a) Reference Scenario *(b) FEP Scenario*

Figure 7-6 Year-on-Year Increase in Capacity Investment based on Annual Demand Increase

In contrast to the investment schedules based on peak power demand, capacity investment based on annual increase in energy demand shows fluctuating year-on-year increase in additional investment needs. Based on the investment schedules in the Reference Scenario as shown in Figure 7-6, the estimated cumulative investment between 2026 and 2035 is about S$96.5 million, which comprises S$9.4 million for power grid related infrastructure expansion, S$15.1 million for quay crane, S$14.4 million for yard cranes, S$39.6 million for OPS, and S$18 million for AGV charging infrastructure. In the FEP Scenario (Figure 7-6), the estimated cumulative investment between 2026 and 2035 is about S$195.7 million. This includes S$19.1 million for power grid related infrastructure expansion, S$30.8 million for quay crane, S$28.4 million for yard crane, S$80.7 million for OPS, and S$36.7 million for AGV charging infrastructure.

For port equipment, the cumulative incremental investment between 2026 and 2035 is projected at S$54.21 million. The total cost savings (combining fuel cost and carbon tax savings) is approximately S$208.71 million under the constant GEF scenario and S$213.1 million under the declining GEF scenario. Under both scenarios, the incremental investment can be fully recovered by around 2030.

For shore power, the cumulative incremental investment between 2026 and 2035 is S$45.99 million. Without accounting for carbon tax, the revenue derived from shore power supply (or electricity sales) is approximately S$12.23 million which implies a payback period of 19 years from 2035 regardless of the assumptions on future GEF trajectories. When carbon tax is added to the calculation due to the use of grid electricity, the payback period is prolonged to 23 years under constant GEF conditions, and to 26 years under the declining GEF scenario, both from 2035. Same as explained in Section 7.3.1, although the payback period became longer under the declining GEF scenario, it also implies that the total carbon tax payment is reduced due to a cleaner grid.

In both scenarios, the year-on-year increase in investment fluctuates rather than following a smooth upward trend, as presented in the earlier section. This reflects the phased nature of port expansion and electrification efforts, where lump sum investments typically coincide with the commissioning of new berths or the large-scale procurement of port equipment.

Annual electricity consumption is strongly influenced by operational factors such as throughput. Although the model projects a continuous increase in annual throughput, the pace of growth varies from year to year. As observed in practice, some years experience stronger growth while others are more moderate. Consequently, the annual increase in electricity consumption also exhibits fluctuations.

In contrast, peak demand is measured on an hourly basis and is less affected by these year-on-year variations. As a result, peak electricity demand shows a steady and consistent upward trend over time.

7.3.3 Inter-Scenario Comparison

The inter-scenario comparison provides a contrasting view on the impacts of electrification on capacity investment schedules and trends in each scenario.

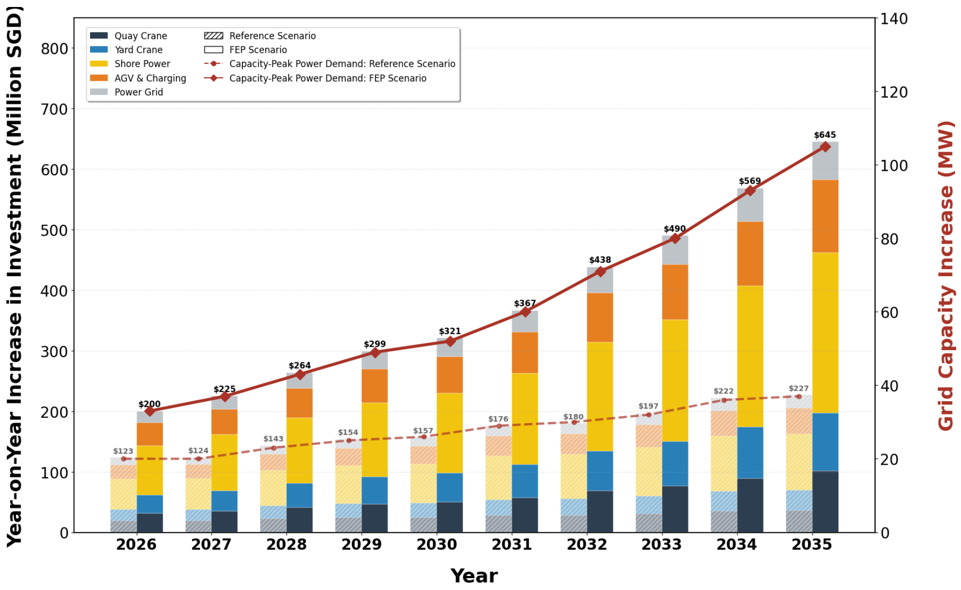


Figure 7-7 Comparison of Investment Needs Based on Peak Power Demand

Achieving full electrification will require a stronger strategic push, characterised by a markedly accelerated pace of capital investment post 2030 (Figure 7-7). By comparison, the Reference Scenario entails a more gradual increase in investment over the same period, reflecting a more conservative development trajectory.

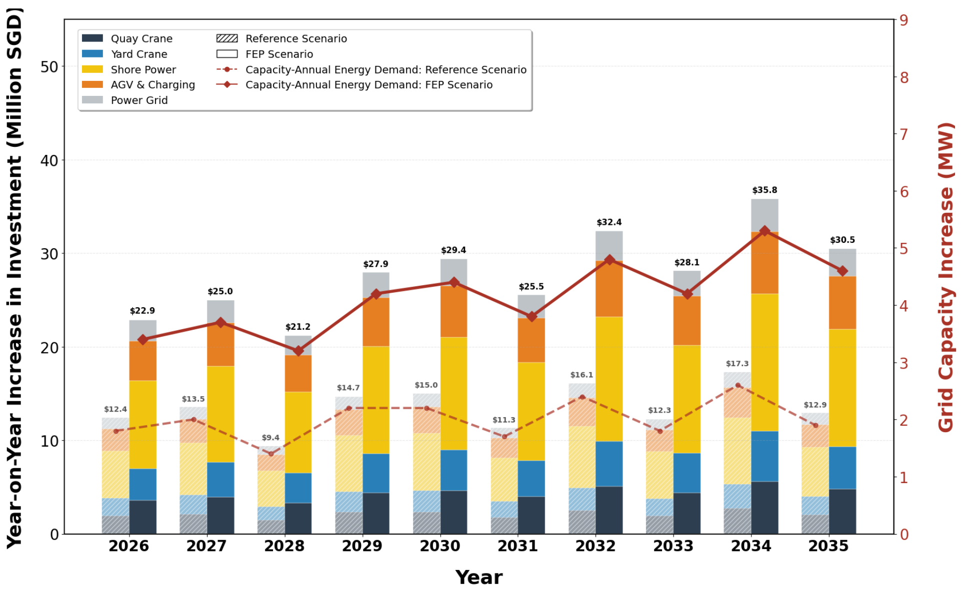


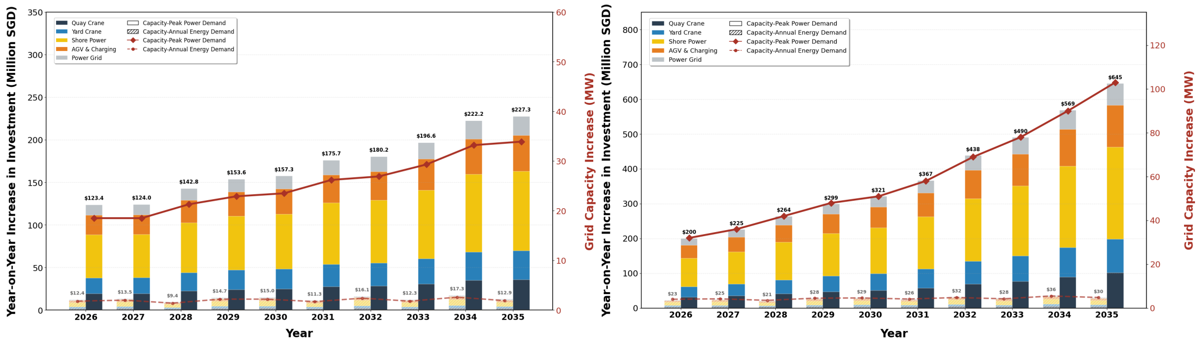
Figure 7-8 Comparison of Investment Needs Based on Annual Energy Demand

Despite the difference in the scale of investment (due to different scale in electrification), the overall trend in the year-on-year increase in capacity investment appears to be consistent between the Reference Scenario and the FEP Scenario (Figure 7-8), likely caused by similar trends in the change in total annual energy demand.

7.3.4 Intra-Scenario Comparison

The intra-scenario comparison provides an alternative view on the differences when planning for new capacity investment for port infrastructure and equipment with consideration for electrification.

As shown in Figure 7-9, modelling results from both scenarios show that infrastructure investments planned solely based on total electricity demand increase could severely understate the actual funding required to meet rising peak power demand. In particular, increased AGV charging requirements and a potential increase in OPS could significantly increase port's electricity demand.



(a) Reference Scenario *(b) FEP Scenario*

Figure 7-9 Comparison of Capacity Investment Trends Based on Peak Power Demand vs Total Energy Demand

8 Policy Analysis

8.1 Current MPA Policy and Initiatives

8.1.1 Macroscopic Fossil Fuel Phase-Out Roadmap

MPA has set a clear phased goal to reduce port terminal emissions by 60 per cent by 2030 compared to the 2005 level and achieve net zero emissions to the whole port by 2050. MPA also has mandatory requirements for in-port operation ships. MPA stipulates that all in-port operation ships must reduce emissions by 15 per cent in 2030 (compared with 2021) and 50 per cent in 2050. This not only involves fixed port facilities but also extends to mobile sources on the water.

8.1.2 Setter of Global Standards

MPA initiated and led the formulation of the TR136 standard, which is the world's first interoperability standard for the charging of electric in-port operating ships, and aims to solve the compatibility problem between different brands of electric boats and charging piles and eliminate technical barriers in the industry.

8.1.3 Economic Incentive Mechanism

MPA implemented the "Green Ship Program" to provide up to 100 per cent initial registration fee reduction and annual tonnage tax special offers for ships that meet environmental protection levels (such as EEDI Excellence, CII A or low-carbon fuel use). MPA has also proposed "port fee preferential treatment". Ocean-going ships using zero-emission fuel can enjoy up to 100 per cent regulatory fee reduction when docking in Singapore, which significantly reduces the economic burden of shipowners' transformation.

8.2 Current PSA Initiatives

8.2.1 Tuas Port Full Power Vision

PSA proposes to build Tuas Port into the world's largest all-electric automated terminal. By 2050, Tuas Port plans to realise 100 per cent electricity-driven status for all container loading and unloading equipment.

8.2.2 Fossil Fuel Phase-Out

The initiative implements a scale change, and PSA proposes to deploy 700 Electric Prime Movers by 2030 to phase out traditional diesel equipment. Since 2015, PSA has continuously invested in the research and development and deployment of rail mounted gantries and minimised the carbon intensity of the container handling process in Tuas Port.

8.2.3 Renewable Energy

PSA, proposes to make full use of suitable roof area within the port for PV panel deployment, and plans to double the solar energy generation to 9 GWh per year by 2030. In response to the potential impacts from high-power fast charging, PSA is also piloting the use of a battery energy storage system for better renewable integration and load management for AGV charging and potential future OPS adoption.

8.3 Policy Recommendations

1. **Phased mandates, cost restructuring, and internationally aligned standards for shore power deployment**

The deployment of OPS should transition from an optional measure to a mandatory requirement through a phased regulatory approach combined with market-based incentives. A clear implementation roadmap should be established, initially requiring vessels to be equipped with shore power reception capabilities, followed by the gradual expansion of mandatory usage, prioritising vessels with longer berthing durations while allowing for differentiated exemptions where appropriate.

From an economic perspective, policies should aim to achieve a “cost reversal” between shore power usage and auxiliary engine generation. This can be realised through dedicated low electricity tariffs for OPS, time-of-use pricing schemes, and fuel-use disincentives such as carbon taxation or port surcharges. Complementary measures including electricity consumption-based subsidies, green port fee reductions, and incentives for frequent users should be introduced to enhance adoption.

In parallel, Singapore should establish a comprehensive and unified technical standard system covering connection interfaces, voltage levels, and frequency specifications, aligned with international standards such as those developed by the International Electrotechnical Commission and Institute of Electrical and Electronics Engineers. Proactive alignment with emerging global regulatory frameworks, including those in key markets such as the European Union, will ensure interoperability, reduce retrofit costs, and reinforce Singapore’s position as a future-ready global maritime hub. Infrastructure planning for OPS should also be integrated into national grid development strategies, prioritising high-activity berths and key green shipping corridors.

2. Integrated infrastructure planning and grid–port coordination

Port electrification should be treated as a national infrastructure and energy system challenge rather than a standalone port-level initiative. A dedicated Port Electrification Grid Integration Taskforce could be established, comprising key stakeholders such as the Maritime and Port Authority of Singapore, the Energy Market Authority, grid operators, and terminal operators. This taskforce should be responsible for conducting comprehensive and regularly updated power demand assessments, including the combined load from OPS and electrified port equipment.

Policy should shift from passive grid expansion to proactive system optimisation. This includes the development of port microgrids integrating photovoltaic systems, shore power loads, and battery energy storage, supported by intelligent energy management systems capable of forecasting vessel arrivals and optimising load distribution. Peak shaving and demand-side management should be prioritised through mechanisms such as maximum demand constraints and demand response programmes.

In addition, ports should explore advanced system flexibility solutions, including Vehicle-to-Grid applications where electric AGVs function as mobile storage units capable of providing ancillary services to the grid. These measures will reduce reliance on costly peak-driven grid expansion while enhancing system resilience and operational efficiency.

3. Blended finance, fiscal incentives and demand-side market creation

To address the high capital expenditure and long payback periods associated with port electrification, a comprehensive blended finance framework should be established to de-risk investment and mobilise private capital. This includes leveraging existing schemes such as the Enterprise Financing Scheme-Green, expanding access to green bonds, green loans, and blue bonds, and introducing enhanced fiscal incentives such as accelerated depreciation and investment allowances.

At the same time, strong demand-side signals must be created to break the “chicken-and-egg” dilemma. The existing Green Ship Programme should be strengthened and extended beyond its current horizon, offering more substantial and long-term port dues concessions for vessels actively utilising OPS. Carbon pricing mechanisms and port-related surcharges can further reinforce the economic case for electrification.

In the near term, transitional instruments such as Renewable Energy Certificates and Virtual Power Purchase Agreements can be leveraged to enable ports to achieve net-zero emissions ahead of full grid decarbonisation. Public funding should also be directed towards pilot and first-mover projects to catalyse early adoption and build investor confidence.

4. Cross-sector demand aggregation and innovative business models

A viable and scalable business case for port electrification requires moving beyond a siloed, port-centric approach towards cross-sector demand aggregation. Policymakers should facilitate the formation of multi-stakeholder consortia that bring together port operators, shipping companies, power generators, and large electricity consumers such as data centres. This model enables shared investment, aggregated demand, and improved utilisation of infrastructure, thereby enhancing overall project bankability.

Innovative business models should be actively promoted to reduce upfront capital burdens and improve financial viability. These include Energy-as-a-Service, Equipment-as-a-Service, and Energy Performance Contracting models, which allow infrastructure and equipment costs to be recovered through long-term service agreements rather than initial capital expenditure.

In addition, operational innovations such as equipment leasing, battery–vehicle separation, and standardised battery swapping systems should be encouraged to improve life cycle cost efficiency and operational flexibility. Such models not only lower barriers to entry but also create new market opportunities across the value chain.

5. **Catalysing innovation, pilot projects, and first-mover deployment**

Targeted public funding and coordinated innovation efforts are essential to accelerate the development and deployment of next-generation port electrification technologies. Policymakers should establish public-private innovation consortia to develop, test, and commercialise advanced solutions, positioning Singapore as a “living lab” for smart and sustainable port technologies.

Key areas of focus should include high-power automated charging systems such as robotic connection arms and pantographs, inductive (wireless) charging technologies, and integrated digital platforms for energy management and operational optimisation. Pilot projects and demonstration sites, particularly within large-scale developments such as Tuas Port, should be used to validate these technologies under real-world conditions.

By supporting first-mover deployments and reducing technological uncertainty, Singapore can not only accelerate domestic adoption but also develop exportable solutions and standards for the global maritime industry.

6. **Future-proofing through energy diversification and system flexibility**

Given the uncertainty surrounding future energy pathways, port electrification strategies should be designed to remain flexible and technology-neutral. Policymakers should avoid over-reliance on a single energy carrier and instead support a diversified approach that balances green electrons with green molecules.

While electrification will play a central role, alternative energy carriers such as hydrogen and other low-carbon fuels may be better suited for certain applications, including heavy-duty vehicles and specialised port equipment. Supporting the development of hydrogen-based systems, including fuel cell-powered vehicles, can complement electrification efforts while enhancing energy security and resilience.

For an import-dependent country such as Singapore, diversification of energy carriers also reduces exposure to supply risks and infrastructure constraints. A flexible, multi-pathway approach ensures that port decarbonisation remains robust under evolving technological, economic, and geopolitical conditions.

7. **Regional integration, green corridors, and standard export**

The realisation of scale effects in port electrification depend on regional coordination and international interoperability. Singapore should take a leadership role in promoting the harmonisation of technical standards, regulatory frameworks, and operational protocols across ASEAN. This includes alignment of voltage levels, connection systems, and safety requirements to reduce retrofit costs and enhance vessel compatibility across regional ports.

At the same time, the development of Green Shipping Corridors should be accelerated to enable coordinated deployment of OPS and other low-carbon solutions along key trade routes. These corridors can serve as early adoption pathways, creating concentrated demand and enabling economies of scale.

By exporting its standards, regulatory frameworks, and best practices, Singapore can strengthen its influence in global green maritime governance while enhancing regional competitiveness and integration.

8. **Global emission attribution, pricing framework, and market design for shore power**

While shore power is widely recognised as an effective solution for reducing greenhouse gas emissions and local air pollutants from vessels at berth, its deployment introduces a critical accounting and market design challenge. Under current international frameworks, emissions from auxiliary engines used by ships during berthing are classified as part of the vessel's fuel combustion and therefore fall under the ship operator's responsibility (typically Scope 1 emissions for the shipping company). However, when ships switch to shore power, these emissions are effectively transferred to the electricity generation source and are consequently accounted for within the host country's power sector (Scope 2 emissions), thereby increasing Singapore's reported emissions inventory.

This creates a structural misalignment between the location of emissions accounting and the beneficiary of decarbonisation. Without corrective mechanisms, ports that invest in shore power infrastructure may face an unintended increase in their national carbon burden, potentially weakening incentives for large-scale deployment.

To address this, a robust emission attribution and pricing framework for OPS should be established. First, transparent metering systems and standardised reporting of grid emission factors should be implemented to accurately quantify the emissions associated with shore power consumption at the vessel level. Second, a mechanism should be developed to reattribute these emissions to ship operators, reflecting the fact that shore power is a direct substitute for onboard auxiliary engine use. This can be operationalised through carbon accounting instruments, contractual arrangements, or digital tracking systems linked to vessel energy use.

From a market perspective, OPS electricity pricing should reflect not only the cost of electricity supply and infrastructure, but also the cost of carbon. A structured tariff framework could include differentiated pricing components, such as energy charges, connection fees, and carbon-adjusted pricing signals, to ensure both cost recovery and behavioural incentives.

In the near term, such emission reallocation mechanisms can be implemented on a bilateral basis between port authorities and shipping companies, supported by contractual agreements and recognised carbon accounting methodologies. Over the longer term, there is a need to advance multilateral or global frameworks, potentially under the International Maritime Organisation, to standardise emission attribution for shore power and enable consistent treatment across jurisdictions. This would support a more coherent decarbonisation pathway, allowing shipping companies to prioritise Scope 1 emission reductions through fuel switching and electrification, while ensuring that Scope 2 emissions associated with shore power are appropriately allocated and incentivised.

By addressing both emission attribution and pricing, this approach can remove structural barriers to OPS adoption, align incentives across stakeholders, and accelerate the decarbonisation of maritime transport without disproportionately burdening host countries.

9 A Proposed 3-Step Approach to Port Electrification

Establish Future Demand Profiles

- A good understanding of the ports today and a robust projection of future demand based on historical insights are critical to establish future demand profiles, especially in capturing peak demand and long-term energy demand evolution.

Establish 24/7 CFE Gap

- A 24-hour modelling of port energy demand should be compared against the 24-hour supply profile of clean energy supply to identify insights on opportunities and challenges to meet 24/7 CFE.

Establish LMET Roadmaps

- In the absence of a fully decarbonised national grid, ports should also establish near- and long-term LMET (Low-carbon Molecule and Electron Technology) roadmaps to decarbonise port's micro-grid. Port's unique position to access floating clean energy solutions should receive priority attention.

10 Conclusion

Singapore's position as one of the world's leading transshipment hubs, handling around 20 per cent of global container transshipment flows, places it in a uniquely influential position to shape the future of maritime decarbonisation in the Asia-Pacific and beyond. As both a global maritime hub and a standards setter, Singapore is well positioned not only to implement port electrification at scale, but also to export technical standards, policy frameworks, and operational models to regional and international ports. This positions Singapore as a potential anchor for advancing coordinated port electrification efforts across Asia-Pacific, supporting the development of green shipping corridors and accelerating global maritime decarbonisation.

This study makes three key contributions. First, it develops and validates a robust AI-based hybrid modelling framework by systematically integrating Wavelet Transform Coherence, Temporal Convolutional Network, and eXtreme Gradient Boosting models. This combined approach effectively captures multi-scale temporal dynamics, operational dependencies, and nonlinear relationships in port energy demand, achieving high predictive accuracy and strong generalisation performance. Second, the modelling results provide a comprehensive quantitative assessment of electrification pathways. Under projected throughput growth of approximately 42.5 per cent, port energy demand is expected to increase by around 43 per cent, reaching over 600 GWh by 2035. Full electrification delivers clear economic and environmental benefits, including cumulative operating cost savings of S$76.5 million and a net advantage of S$38.95 million over the Reference Scenario, alongside substantial emissions reductions, including the complete phase-out of fossil fuel use and elimination of local air pollutants by 2035. Third, the study highlights critical system-level implications, particularly the strong coupling between electrification, operational scale, and peak electricity demand, with peak loads increasing by more than 3.5 times under full electrification.

From a decarbonisation perspective, phasing out fossil fuel-powered equipment represents a direct and effective pathway to reduce emissions from port operations. However, electrification also shifts energy demand onto the power system, creating additional pressure on grid infrastructure. The analysis suggests that while this increase in demand is significant, it remains manageable with proper planning, including grid reinforcement, energy storage deployment, and demand-side management. Similarly, the large-scale deployment of shore power is technically feasible and represents a critical enabler for reducing vessel emissions at berth. However, it also introduces a structural shift in emissions accounting, whereby emissions from international shipping activities are effectively transferred to the domestic power sector.

This raises an important policy challenge regarding emission attribution and cost allocation. To ensure the effective and equitable deployment of shore power, it is essential to establish clear mechanisms for emissions accounting, carbon pricing, and electricity tariff design. This includes addressing how emissions associated with international vessels are allocated, how carbon costs are shared between ports and ship operators, and how shore power electricity pricing can be structured to incentivise adoption while maintaining economic competitiveness. Without such mechanisms, the full environmental and economic benefits of shore power may not be fully realised.

Overall, Singapore’s leadership in maritime decarbonisation relies on policy-driven market creation. Electrification, while central for port operations and short-distance shipping, is complemented by zero-emission fuels for deep-sea shipping. Regulatory signals, mandatory OPS, and carbon pricing form the foundation that makes infrastructure investment bankable and economically viable. By integrating policy, technology, and market mechanisms, Singapore can accelerate port electrification, develop green shipping corridors, and serve as a regional anchor for maritime decarbonisation. Electrification investments are therefore not only technically necessary but also strategically enabled by a clear regulatory and market framework.

List of Abbreviation

AGV	Automated Guided Vehicle
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
FEP	Fully Electrified Port
GEF	Grid Emission Factor
GHG	Greenhouse Gas
GWh	Gigawatt hour
IMO	International Maritime Organisation
kt	kilotonne
kW	Kilowatt
kWh	Kilowatt-hour
MPA	Maritime and Port Authority of Singapore
MW	Megawatt
NO_x	Nitrogen Oxides
OPS	Onshore Power Supply
PEMA	Port Equipment Manufacturers Association
PM	Particulate Matter
PV	Photovoltaic
REC	Renewable Energy Certificate
SO_x	Sulphur Oxides
TCN	Temporal Convolutional Network
TEU	Twenty-foot Equivalent Unit
WTC	Wavelet Transform Coherence
XGBoost	eXtreme Gradient Boosting

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