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Green Shore Power Supply at Ports: A Comparative Engineering Assessment Using Bounded Energy Envelopes

Venkata Ramana Akkaraju
Chairman, New Mangalore Port Authority, Karnataka, India

* Corresponding Author: **Venkata Ramana Akkaraju**

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Abstract
Shore-side electricity (shore power) is an essential step to the minimization of emissions at berth of ships, but its engineering viability is determined by variety across ports because of vessel mix, turnaround, traffic density and energy infrastructure. This paper gives a comparative engineering evaluation of the green shore power supply under a limited energy- envelope by basing solely on the openly available data on the operations of the ports. Three large Indian ports which are typological representations of varying modes of operation: container-based, bulk, and diversified are examined. With literature reported ranges of auxiliary power demand, average vessel turnaround times are added together to form indicative per-call shore power energy envelopes without the use of proprietary vessel load data.

The findings demonstrate that container hubs have a comparably low per-call energy demand (around 44-112 MWh per vessel call), which is caused by short berthing times, but a large aggregate annual demand caused by vessel calls. Conversely, bulk- and tanker-dominated ports have significantly more energy demand per call (around 70-360 MWh per call), due to relatively long berthing times, whereas diversified ports demand flexible and modular solutions, to support the heterogeneous profile of vessels. Electrical infrastructure analysis suggests that ports that have a high-voltage grid redundancy and large renewable energy infiltration are in a more advantageous situation to adopt low-carbon shore power at scale.

Keywords: Green shore power, Port electrification, Vessel turnaround time, Auxiliary power demand, Auxiliary power demand

1. Introduction

Seaports are the key in international trade and the growth of the region and they are the important nodes that link the maritime transport with the inland logistic systems. Meanwhile, port operations have important externalities, such as the emission of ships at berth, cargo-handling equipment and the hinterland transport, which are spatially agglomerated in port cities. As indicated in the initial sustainability-based port research, port authorities become more and more expected to balance between economic development and environmental conservation and social responsibility, which is a central pillar of sustainable transport development (Kotowska, 2016) [3].

Ships at berth can be considered one of the most difficult types of emissions related to ports. Their contribution to overall emissions of shipping in the sea will be lower, but they emit close to densely populated cities which increases local air-quality, health, and noise effects. Shore-side power Shore power, also known as shore power or cold ironing, has hence become a prominent application of mitigation, allowing vessels to turn off onboard auxiliary diesel generators when berthing. Experiments in individual ports have shown that shore power can also be used in combination with renewable energy sources to effectively decrease the emission of particulate matter and carbon dioxide when hoteling is involved (Kotrikla *et al.*, 2017) [4].

Alongside the development of shore power, an increasing literature has reviewed the expanded role of port authorities in controlling the movement of energy, as well as incorporating sustainability into the port process. Acciaro *et al.*, (2014) [1] point out the fact that ports are typified by geographically concentrated activities of energy demand and supply, which are the port authorities that can be effective coordinators of energy management strategies. Their discussion of European ports shows that active energy management can enhance efficiency, generate new sources of revenue and enhance port competitiveness. Nevertheless, these studies are mostly theoretical or policy-focused, which provide minimal engineering-grade information on the impact of the features of operational ports on the viability of a shore power implementation.

Another body of research has centered on renewable energy technologies that can be used to facilitate green port. Vertical-axis wind turbines (VAWTs), such as Savonius-type and helical-blade, were also studied by numerous researchers, as they could be suitable in urban and low-wind settings where their simple construction, omnidirectional wind-acceptance, and low operational speed are important (Han *et al*., 2018; Mahmoud *et al*., 2012; Zhu *et al*., 2016) [2, 5, 8]. Although these works can be useful in the study of the aerodynamics of turbines and optimization of their performance, they are more of the component level or laboratory level analysis and do not focus on the system level integration of the renewable energy into the port electrical networks or shore power supply schemes.

Equally, the studies on green port infrastructure have been inclined towards the electrification of cargo-handling equipment including electric rubber-tired gantry cranes showing significant energy savings and reduction of emissions relative to diesel-powered counterparts (Yang & Chang, 2013) [7]. Along with the practical implementation studies, including those that were carried out in the Port of Koper, virtual examples of how pilot projects and equipment upgrades may aid in overall port energy efficiency and reduction of emissions (Pavlic *et al*., 2014) [6]. Nevertheless, such studies are usually aimed at terminal operations, but not vessel hoteling and never specifically examine the interrelationship between vessel traffic properties, berth occupancy and shore power energy demand.

Although there is increasing interest in shore power and renewable energy at ports, the available literature indicates that two important gaps exist. First, a lot of studies take an extremely site-specific perspective relying on in-depth operation information or even simulation assumptions, which constrain the extrapolability of their results to other ports. Secondly, comparative, engineering-based measurements that can associate the basic indicators of port operations, including vessel turnaround time and traffic composition, with power energy demand on shore in a clear and data-conservative way are lacking. This disparity is especially large in situations when the electrical load data at the vessel level is not publicly available.

To overcome these constraints, the current paper elaborates a comparative engineering evaluation of green shore power provision based on publicly available port data and auxiliary power need ranges based on literature. The study provides a constrained energy-envelope methodology which connects berthing time of vessels with auxiliary power requirements as the way to evaluate the feasibility of shore power without excessive dependence on localized assumptions by analyzing three large Indian ports with varying operational archetypes. By doing so, the paper will supplement the current policy, technology and case-study literature by offering a framework of the system, which will enable transferable conclusions to be made relating to shore power implementation in ports.

2. Literature Review

2.1. Policy, Regulatory, and Governance Perspectives on Shore Power

The recent literature has highlighted the role of regulatory and governance mechanisms in speeding up the shore power adoption. The review of legal aspects of the changing shore power framework in China, as noted by Wang (2024) [20], shows the shift in the pattern of incentive-based industrial policies into the force and necessitation of mandatory laws with penalties. This paper shows that regulatory strictness may have a substantial effect on adoption, but does not cover the technical or operation aspects of these mandates and the energy demand in ports due to shore power. In the same vein, the research on green port governance and stakeholders involvement places important weight on institutional functions and perception-based obstacles (Kumar and Yadav, 2026; Zhuang *et al*., 2025) [14, 23]. Although these contributions serve well to comprehend how adoption works, still, these are largely disconnected to engineering-level feasibility analysis and fail to connect policy goals with port-specific electrical or operational limitations.

2.2. Shore Power as an Emission Mitigation Measure at Ports

Site-specific case studies give empirical evidence that shore power is an effective emission mitigation measure. According to Kotrikla *et al*. (2017) [4], with electricity on shore and renewable energy, a large portion of ship emissions at port can be removed, as evidenced by a thorough analysis of the vessel activity at the port of Mytilene. Although this research proves the benefits of shore power to the environment, its application is limited by the granularity of vessel call information and theoretical simulation to other ports that do not have these data points. Even more recent optimization-based and policy-oriented works also presuppose the availability of a priori a shore power demand profile, and are interested in the incentivization or scheduling of shore power (Luo *et al*., 2024; Zhong *et al*., 2024) [22]. As a result, the key question underlying the scale of the demand of shore power energy under the influence of the characteristics of port operation is not sufficiently answered.

2.3. Renewable Energy and Advanced Energy Systems for Green Ports

There is an extensive literature covering the use of renewable systems and multi-energy systems as a route to zero-carbon ports. The offshore energy island and multi-energy coupling researches suggest highly-integrated systems combining wind, solar, hydrogen, ammonia, and methanol energy generation, which are facilitated by techno-economic optimization models (Su *et al*., 2026) [18]. The off-grid renewable hubs, which are researchable in relation to hydrogen-powered ships, are in turn investigated in complementary research and emphasize on the economic viability of wave-wind hybrid systems (Kheirani *et al*., 2025) [13]. Although these studies can be applied to the future design of low carbon energy infrastructures, they are system optimization-oriented and operate under assumed demand conditions, not adjusted to estimate the feasibility of shore power at current ports with heterogeneous vessels traffic and limited publicly available data.

The optimization paradigm is further advanced in the Port integrated energy system (PIES) research that integrates ships, automated guided vehicle, storage systems, and renewable generation using multi-objective algorithms (Peng *et al*., 2025) [16]. These methods are quite effective and cost-efficient and based on high-resolution load and operational data, which limits their applicability as generalized feasibility assessment tools.

2.4. Optimization, Artificial Intelligence, and Port Energy Management

The new developments in optimization and artificial intelligence have facilitated complex energy management policies of green ports. Conte *et al.* (2025) [11] use reinforcement learning and model predictive control to maximize shore power and renewable energy dispatch and achieve almost complete removal of the diesel consumption at berth when the conditions are under particular operations. On the same note, mixed-integer programming and game-theoretic models are used to study berth allocation, equipment deployment, and incentives to adopt ship shore power and hydrogen (Zhang *et al*., 2024; Zhong *et al*., 2024; Nikkhah *et al*., 2024) [21, 22, 15]. Such contributions can be useful in optimization of operations; but they assume that the magnitude of the shore power demand and infrastructure capacities are already determined, thus putting themselves after the feasibility determination.

3. Methodology

This paper utilizes a comparative, case-study-based engineering approach to assess the viability and system-level consequences of green shore power supply in ports. The methodology framework is intended to provide quantitative rigor without conflict with the constraints of the publicly available port data. Instead of seeking detailed operational forecasting or economic optimization, emphasis is placed on engineering feasibility, limited energy estimations and comparative system analysis, which are suitable when port infrastructure of large scale is studied.

3.1. Case Study Selection

The three important ports in India, which include Chennai Port Authority, Deendayal Port Authority, and Jawaharlal Nehru Port Authority (JNPA) were used as representative case studies due to their clear different operational archetypes evident in the entire national port system. Chennai Port is an urban, diversified, mixed-cargo port; Deendayal Port is a high-tonnage port that consists of bulk and tanker activities; and JNPA is a container mega hub with very high vessel-call frequency. Collectively, these ports now represent a large range of vessel mixes, turnaround durations, grid capacities and renewable energy plans making generalisable conclusions about the design of shore power systems.

3.2. Data Sources and Data Classification

The analysis uses only publicly available and verifiable sources of data, such as port authority annual reports, official operational statistics, publications released by the Ministry of Ports, Shipping and Waterways, international benchmarking research, and tender-level disclosures related to electrical and renewable infrastructure. Directly reported operational indicators of the port authorities, i.e. cargo throughput, container volumes, turnaround times, and grid connection levels are used without any modification. In situations where the information of vessel-level or port-wide auxiliary power demand is not available, the paper uses literature-based auxiliary power demand ranges based on peer-reviewed maritime engineering studies and IMO technical evaluations.

3.3. Operational Indicators and Traffic Characterization

The operational characteristics which are operational in assessing shore power viability are assessed through the indicators that reflect a combination of both in terms of scale and time series characteristics, i.e., cargo throughput, container traffic, the type of dominant vessels, vessel-call frequency, and the average vessel turnaround time. The intensive variables are used to form vessel-call intensity based on qualitative categories and do not impose unsubstantiated numerical assumptions. Turnaround time is considered as the major time parameter of duration in which the shore-side supply can supersede onboard auxiliary diesel generation in vessel hoteling.

3.4. Electrical Infrastructure and Grid Readiness Assessment

Electrical preparation of shore power installation is determined through the observation of the design and strength of the electrical construct of each port, incoming grid voltage level, internal distribution structure, and the level of supply redundancy. This test is based on topology and adequacy of capacity of the system, as opposed to the finer detail of electrical design, and is aware of load-flow analysis and coordination of protection as something that is beyond the data of public knowledge. The aim is to determine whether or not each port has the underlying electrical infrastructure necessary to enable shore power integration on a large-scale basis.

3.5. Bounded Engineering Formulation for Shore Power Energy

A limited engineering model of the quantitative evaluation of shore power potential is presented, where the electrical energy that is provided by a shore per call of a single vessel is formulated as the product of auxiliary power demand and berthing time. By relying on bounded energy envelopes derived from publicly available indicators rather than proprietary high-resolution datasets, the proposed methodology prioritizes model agility over data dependency, enabling comparative feasibility assessment across ports with diverse operational archetypes (Tasleem *et al*., 2024). The requirement of auxiliary power is an interval instead of an absolute value, which shows the differences in the size of the vessel, on-board systems, and the mode of operation. This formulation provides envelopes of energy and point estimates; this guarantees the results by being conservative and physically realistic, as well as allows relevant comparisons between ports with varying operational profiles.

4. Results and Discussion

This section is a revised, quantitative-comparative analysis of the practicability of green shore power supply in three large Indian ports: Chennai Port Authority, Deendayal Port Authority, and Jawaharlal Nehru Port Authority (JNPA). The analysis incorporates reported operational indicators, benchmark turnaround times, vessel traffic characteristics, electrical infrastructure preparedness and renewable-energy integration with limited engineering relationships used to produce estimates of shore-power energy envelopes without references to non-public proprietary information.

4.1. Operational Scale and Vessel Traffic Characteristics

The three chosen ports, Chennai Port Authority, Deendayal Port Authority and Jawaharlal Nehru Port Authority (JNPA) are the different types of operational model in Indian port system. The difference in the scale of operations, cargo make-up, and vessel traffic pattern are the focus of the consideration of the port-specific feasibility and design demands of green shore power systems.

Chennai Port is a diversified urban port, and it manages a vast range of vessel types such as container vessels, automobile carriers (Ro-Ro/PCC), bulk carrier, tanker vessels, and heavy-lift/project cargo vessels. Such a variety is a very direct outcome of the long-standing fact that the port is an industrialized hinterland general cargo gateway. Table 1 illustrates that Chennai has a medium sized total traffic in terms of cargo throughput of about 55 MMT, and 1.6-1.8 million TEUs of container traffic. Its annual vessel calls are not monopolised by one type of ship but at the same time the presence of different types of vessels suggests heterogeneous auxiliary power demand profiles and the requirement to have flexible and adaptable shore power system arrangements.

Deendayal Port, on the contrary, could be considered as a high tonnage, bulk oriented type of operation. It is the largest port in India in terms of the total cargo throughput, of over 108 MMT, with cargo streams of liquid bulk (crude oil and petroleum products) and dry bulk (coal, iron ore, salt, fertilizers) as the driving forces. Table 1 provided in the summary shows that container throughput in Deendayal Port is small, and the majority of the vessel traffic consists of tankers and bulk carriers. These classes of vessels are generally distinguished by longer berthing times, and long-lasting use of an auxiliary engine when loading and unloading cargo, and so Deendayal Port is specifically of relevance when the frequency of vessel-call is low compared with main hubs with containers, but the cargo capacity of each vessel and its berthing duration is high.

JNPA is a third and opposite archetype: a container based mega hub with extremely high vessel-call frequency. Managing an estimated 7.9 million TEUs each year and almost 92 MMT of overall cargo, JNPA represents an estimated 50 per cent of Indian containerized trade. According to Table 1, the port is receiving approximately 3,900 or more vessel calls annually, mostly container vessels, which are calling at very automated terminals. Even though the berthing time in JNPA is relatively short in comparison with bulk-friendly ports, the incredibly high frequency of the vessel calls causes a massive cumulative auxiliary power demand, with fast-connection, high-throughput shore power systems Modeled based on fast plug-in and disconnection.

Table 1: Operational scale and vessel traffic profile of the case study ports

Parameter	Chennai	Deendayal	JNPA
Total cargo throughput	~55 MMT	>108 MMT	~92 MMT
Container throughput	~1.6–1.8 M TEUs	Limited	~7.9 M TEUs
Annual vessel calls	High (mixed)	High (bulk/tanker)	~3,900+
Dominant vessel types	Containers, car carriers	Tankers, bulk carriers	Container ships

According to Table 1, Deendayal Port ranks top in the number of tonnes of cargo, JNPA ranks top in vessel-call frequency, and Chennai Port is the most diverse in the types of vessels. These differing operational features directly affect shore power systems demands: capacity-oriented at bulk ports, throughput-oriented at container hubs and flexible and multi-vessel at diversified urban ports. This establishes that the strategies of deploying shore power should be port specific to the nature of traffic as opposed to the same approach across ports.

4.2. Vessel Turnaround Time and Berthing Duration

An important parameter of operations that determines the efficacy of shore power systems is vessel turnaround time (TAT), in that it determines the longest continuous period, after which shore-side power may substitute on board auxiliary diesel generation during hoteling.

In Chennai Port Authority the average TAT has been reported to be about 2.03 days ([?]49 h). This comparatively prolonged berthing time is a characteristic feature of the mixed cargo structure of the port and allows the long displacement of auxiliary engines, which is especially valuable in an urban port environment where local air-quality effects are also important.

Deendayal Port Authority records an average TAT of 54.24 h in FY 2023-24 and provisional value of an average of 60.22 h in FY 2025-26. Such values are also the highest in major Indian ports, and greatly affected by the preeminence of the port in bulk and liquid cargo working. Such long berthing periods, as listed in Table 2, have the effect of enhancing the per-vessel potential of shore power consumption and preferring large capacity, long-duration electrical links.

Conversely, Jawaharlal Nehru Port Authority (JNPA) has benchmark operational efficiency and the TATs of container vessels are usually within the range of around 22-28 h (0.9-1.1 days) and the mean of around 1.10 days. Despite the constraints of shorter berthing times on per-call shore power energy, the extremely high vessel-call frequency of JNPA will maintain a significant aggregate shore power opportunity, with fast-connection and high-throughput systems being essential.

Table 2: Average vessel turnaround time (TAT)

Port	Average TAT	Dominant implication
Chennai	~49 h	Long continuous hoteling
Deendayal	~54–60 h	Very long bulk/tanker stays
JNPA	~22–28 h (containers)	Short, high-frequency calls

Table 3 that shows the cargo-wise TATA data in Deendayal Port indicates that the heterogeneity between the categories of vessels is significant. Container ships have quite low turnaround time (~29.16 h), whereas liquid bulk vessels remain at berth for ~42.48 h. Dry bulk vessels have much longer berthing periods (~71–117 h), especially when under mechanized handling whereas the breakeven vessels have the longest stays of more than ~127 h.

Table 3: Cargo-wise turnaround time at Deendayal Port

Cargo type	TAT (hours)
Container	29.16
Liquid bulk	42.48
Dry bulk (conventional)	71.52
Dry bulk (mechanized)	117.12
Break bulk	127.20

Tables 2 and 3 demonstrate that the bulk- and break-bulk-dominated vessels may face a two- to fivefold longer berthing time than containers, which are essentially significant in terms of shore power system demand. Long-stay bulk ports prefer high-capacity, sustained shore power supply and high-efficiency container hubs, high-throughput architectures need to be rapid-connection. The findings confirm that turnaround time is a key factor of shore power and that systems should be designed specifically to the port and cargo as opposed to being put into general use.

4.3. Bounded Engineering Relationship for Shore Power Energy

In order to bring a rigor of quantitative type but keeping in mind the constraints of port and vessel data that are available publicly, the maximum shore power energy delivered to a vessel during one port call is represented by a constrained engineering relationship. This expression can be used to compare ports and vessel types without using proprietary or non-disclosed operational metrics.

The shore power energy per vessel call is defined as:

$$E_{SP} = P_{aux} \times T_{berth}$$

Where

E_{SP} represents the electrical energy supplied from shore during a single berthing event,

P_{aux} denotes the auxiliary power demand of the vessel, and

$T_{berth}$is the reported average berthing duration.

In this formulation, P_{aux} auxis is not considered as a constant value but rather a limited quantity that shows the change in the size of vessels, systems on board, the mode of operation and the handling of cargo. The use of auxiliary power demand ranges is based on international literature on the water and IMO technical assessment, which reliably indicate characteristic auxiliary load envelopes across the various classes of vessels in hoteling.

Table 4: Typical auxiliary power demand ranges by vessel type

Vessel type	Auxiliary power range (MW)
Container ship	2 – 4
Car carrier (Ro-Ro/PCC)	1.5 – 3
Bulk carrier	1 – 2
Tanker	1.5 – 3
General cargo / project	1 – 1.5

The bounded auxiliary power ranges are used to make sure that the generated shore power energy estimates are conservative and physically real, and not false precise. Together with the port- and cargo -specific berthing times in Section 5.2, this association offers a consistent framework of assessing comparative shore power demand intensity among the various port archetypes.

Notably, the method does not strive to estimate precise values of energy consumption at the port level. Rather, it defines a range of engineering of which the demand of power at the shore is likely to vary, and meaningful comparison of ports with different operating profiles can be made. These constrained formulations are normally used when conducting high impact engineering research in the lack of granular operational information that would determine the system level feasibility.

4.4. Estimated Shore-Power Energy Envelope

Based on the engineering relationship that was presented in Section 5.3, indicative shore-power energy envelopes per vessel call are obtained through the integration of literature-reported auxiliary power ranges and measured average berthing times. This range-based method enables to quantitatively compare across ports without the need to use non-public operational measures.

The resulting bounds on the energy delivered, summarized in Table 5, are physically realistic limits of the extent of electrical energy that may be delivered on shore during a single berthing event at each port.

Table 5: Indicative shore-power energy envelope per vessel call

Port	Dominant vessel type	T_{berth}(h)	E_{SP} range (MWh / call)
Chennai	Container / car carrier	~49	~75 – 196
Deendayal	Bulk / tanker	70 – 120	~70 – 360
JNPA	Container	22 – 28	~44 – 112

Table 5 results reveal clearly some significant differences in per-call shore-power requirements across the three port archetypes. The highest per-call energy envelope is observed in deendayal port due to long berthing time of bulk as well as tanker operations. JNPA on the other hand, experiences the lowest per-call energy demand which is indicative of the short container-vessel turnaround times. Chennai Port lies in the middle of the range with medium to high energy requirements caused by increased hoteling and mix vessel profile.

JNPA has the lowest per-call shore-power envelope although its vessel-call frequency is very high suggesting a high aggregate shore-power potential annually. On the other hand, Deendayal Port is typified by high per-call energy demand, with preference to smaller but greater capacity shore-power connections. These findings affirm that design of shore-power systems should find a balance between the intensity of energy in per-call and vessel-call frequency, and not on a common deployment strategy to be used in different ports.

4.5. Electrical Infrastructure and Grid Readiness

The capability to implement the deployment of the large-scale green shore power is fundamentally limited by the strength, dependability, and configurability of the port electrical infrastructure. The overall ability to deliver power safely and continuously to berthed vessels, whether shore power or internal distribution, and supply redundancy is the determining factor on whether berthed vessels can safely and continuously receive power to support the port operations. The grid readiness of the three port cases in the study is different but sufficient, as they have different operations and developmental paths.

The Chennai Port Authority has an internal electrical network which is based on HT to handle a large assortment of the port activities like quay cranes, cargo-handling devices, terminal functions, lighting and other auxiliary services. The distribution of power is mainly done by 11 kV network and low voltage networks and these are common characteristics of mature urban ports with limited space availability. Although the grid connection is fine in the present state of operation, the moderate degree of redundancy means that shore power integration at Chennai Port will need to be managed in terms of loads and take time to add more ship-side electrical loads at peak operational times.

Deendayal Port Authority, in contrast, is supplied by the Gujarat state grid (GETCO) at 66 kV, and supplies that power to a wide internal 11 kV network of substations, most of which are in the process of being upgraded. This type of infrastructure design is indicative of the bulk and liquid cargo hub characteristic of the port and where high and sustained electrical loads are typical. The fact that the internal distribution capacity is relatively high and that it is in the process of upgrading suggests that it is technologically prepared to support high-capacity shore power systems, especially those meant to supply bulk carriers and tankers with a longer period to stay at the berth.

Jawaharlal Nehru Port Authority (JNPA) has the strongest electrical set up of the three ports. The port receives supply through two independent 220 kV express feeders and the level of supply reliability is very high. Power is fed at a Master Unit Substation (MUSS) and reduced to 11 kV, 6.6 kV and 415 V to allow flexible distribution to containers terminals, logistics facilities and supporting services. This multi-voltage design coupled with high redundancy gives an electrical environment that is very favorable to fast-connection and high-throughput shore power systems, in line with the JNPA container-dominated and fast-frequency vessel traffic.

Table 6: Electrical infrastructure readiness of the case study ports

Parameter	Chennai	Deendayal	JNPA
Grid connection	HT grid	66 kV	Dual 220 kV
Internal distribution	11 kV / LV	Extensive 11 kV	11 kV / 6.6 kV / LV
Supply redundancy	Moderate	High	Very high

According to Table 6, all three ports have the lowest grid connectivity and internal distribution capability to deploy shore power with varying degrees of strength. The dual 220 kV supply of JNPA and its multi-voltage distribution offer the greatest resilience and flexibility, the 66 kV supply of Deendayal, and the growing network allows the high-capacity long-duration shore power and the narrow space of Chennai require compact and managed shore power integration. These variations affirm that the preparedness of electrical infrastructure is the primary factor that defines the structure and design of shore-based power systems, and supports the necessity of port-specific design, instead of homogeneous design.

4.6. Renewable Energy Integration and "Green" Qualification

The degree to which shore power conveys actual decarbonization advantages relies on the intensity of carbon of the electricity provided by shore, and thus the assimilation of renewable energy is a vital element in defining whether shore power may be regarded as green.

Among the ports presented in the case study, Deendayal Port Authority is the most prepared in terms of renewable. This is in the process of making the port a power-surplus facility, the development of a nearly 20 MW hybrid wind-solar power plant is in its support. When calculated on an annual basis of energy balance, it is projected that planned generation of renewable will surpass internal auxiliary generation of power, allowing the shore power to be supplied with minimal dependence on fossil-based grid generation.

Jawaharlal Nehru Port Authority (JNPA) has a high and growing renewable percentage, having about 4.1 MWp of installed solar power and about 50 percent of renewable penetration which will be increased up to 60 percent by 2030. Besides this, the JNPA Special Economic Zone is powered by a 100kWh of renewable power through wind power purchase agreements, which means that large-scale sourcing of renewable power to serve shore power in container terminals is possible.

Chennai Port Authority, on the other hand, shows an average level of renewable integration by being limited by a small amount of land in a compact city setting. However, according to studies, solar photovoltaic potential is about 5-8.65 MWp, which can be used to partially supply renewable. A full self-sufficiency rate of renewable energy is not attainable in the near future, but the introduction of power at Chennai Port on the shore would achieve significant leisure local emissions during long vessel berthing.

Table 7: Renewable energy readiness and green shore power potential

Port	Renewable status	Green shore power potential
Chennai	Moderate, space-limited	Medium
Deendayal	Power-surplus (annual)	Very high
JNPA	High, expanding	High

The integration of renewable energy drastically makes a distinction between the three ports according to the potential of green shore power as recapped in Table 7. Deendayal Port offers the most straightforward route to entirely renewable-linked shore power, JNPA emphasizes a gradual process of decarbonized shore power on a large scale, and Chennai Port points to the complementary significance of the air-quality benefits of the place with renewable growth. These findings prove the fact that the renewable sourcing is the precondition under which the shore power could be considered as green and needs to be assessed along with the characteristics of operational and electrical infrastructure.

4.7. Integrated Comparative Assessment

A systematic comparison across the three ports of the case studies reveals the combination of operational performance and vessel traffic, electrical infrastructure, and integration of renewable energy as defining the appropriateness of green shore power system. In order to harmonize these multi-dimensional findings the turnaround time, vessel-call intensity and range-based shore power energy envelopes are analyzed in a comparative context.

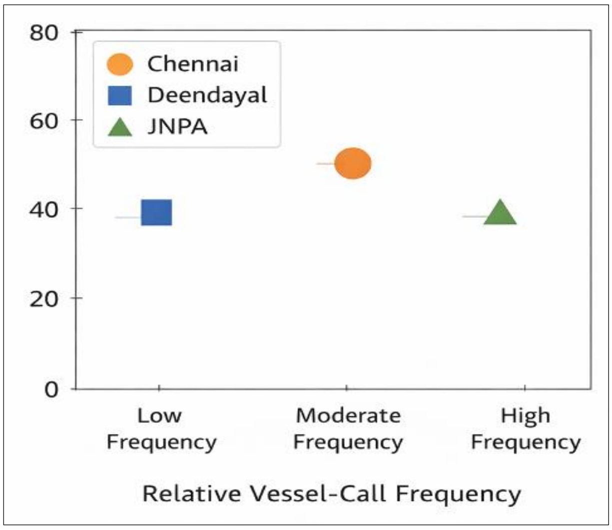

Fig 1: Average vessel turnaround time versus vessel-call intensity for the three ports

Figure 1 shows that there is a correlation between reported average turnaround time (TAT) and relative intensity of vessel-call relative to the three ports. The berthing duration in Chennai and Deendayal Ports is also long with medium call intensity and high, but in JNPA, the turnaround time is very short and the call frequency is very high. This difference ascertains that the power of shore power emergence is driven by various operating models: the duration-dominated use at bulk and mixed ports and the frequency-dominated use at mega hubs of containers.

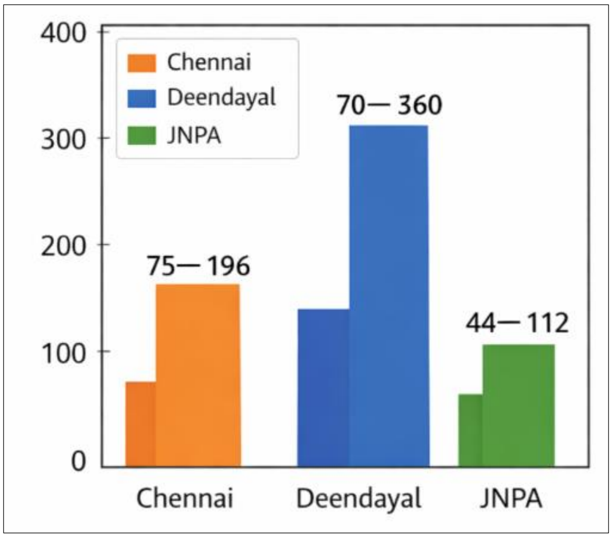

Fig 2: Indicative shore-power energy envelope per vessel call across ports

Figure 2 shows the range-dependent power energy envelope of a vessel call created using the bounded engineering relationship in Section 5.3 and is summarized in Table 5. Deendayal Port has the greatest per-call energy envelope, indicating long berthing times of bulk and tanker ships. Chennai Port is in the middle and JNPA has lowest per-call energy envelope, which is expected by its short turnaround container-vessel turnaround times. These findings highlight that the intensity of per-call energy cannot be used to define the potential of shore power without referring to the frequency of vessel calls.

Table 8: Dominant drivers of green shore power suitability

Port	**Primary driver**	**Shore power system implication**
Chennai	Long berthing duration and urban exposure	Continuous, compact systems
Deendayal	Long bulk/tanker stays and renewable energy surplus	High-capacity, renewable-linked systems
JNPA	Very high vessel-call frequency	Fast-connection, high-throughput systems

Table 8 combines the important results of Sections 5.1-5.6 as it determines the most compelling forces that regulate the suitability of power supply on shores at every port. The mixed traffic nature and long berthing durations in a congested city environment at Chennai Port supports sustained power supplies on shore using compact systems since space is limited. The high capacity shore power systems are closely associated with the renewable generation elements that are supported by bulk- and tanker-dominated operations of Deendayal Port and the surplus of renewable energy at annual basis. Conversely, the characteristics of container-based, high-frequency traffic at JNPA require fast-connection, high-speed and resilient shore power designs that can be easily deployed within the narrow berthing periods.

The combined test shows that the suitability of green shore power does not necessarily depend on one operational measure, but rather the correlation between the berthing time, frequency of vessel calls, strength of electrical infrastructure, and the renewable energy resource. The results prove that standardized approaches to shore power deployment are not optimal, and the particular design of the system is required to achieve the maximum of environmental and operational advantages.

4.8. Discussion

The comparative analysis has shown that the shore power viability at ports is dictated by the interaction of vessel turnaround time, the type of vessel as well as the frequency of calls rather than cargo throughput alone. Container-intensive ports like JNPA have short berthing times and thus reduced per-call shore-side power energy needs; though the frequency of vessel calls is so large that the cumulative system-wide electricity demand is enormous. This operation profile would prefer high throughput and fast-connection shore power systems where the connection efficiency and continuity in operations is of higher importance than the individual connection capacity.

Conversely, bulk and tanker-dominated ports like Deendayal have long berthing times especially on dry bulk and break-bulk vessels, and the per-call energy demand envelopes would be much larger. These circumstances require less but larger capacity shore power connections which have the ability to support long-term auxiliary loads. Chennai Port is a hybrid type of turnaround with a moderate turnaround time, and a very diversified vessel mix, which creates heterogeneous auxiliary power demands. Such diversity supports adaptable and modular shore power designs which can be used across different vessel types to support different voltage, capacity and connection requirements.

One of the contributions of this research is the application of a limited-energy-envelop methodology to determine the viability of shore power in the field of insufficient data. The methodology allows false precision to be avoided, though enough resolution is preserved to distinguish different port archetypes and establish the dominant design drivers, by expressing the auxiliary power demand as literature-based ranges, instead of fixed values. The findings validate this claim by showing that early-stage engineering evaluation and strategic planning can be reasonably supported with such limited estimation, especially in the situations when proprietary information about the vessel-level electrical data are not present. In engineering terms, this conservative formulation makes it robust and easier to transfer, and phased deployment and scalable infrastructure planning, instead of speculative system sizing.

The availability of electrical infrastructure also preconditions the possibility of implementing shore power. Each of the three ports has an internal distribution network and a high-voltage grid connectivity allowing the electrification, however, the readiness profiles vary significantly. The two 220 kV feeders at JNPA offer high degree of redundancy and scalability, thus enabling large scale deployment of shore power with minimum upstream reinforcement. The large 11 kV distribution network of Deendayal Port and its current substation renovations are capable of supporting high-capacity shore power applications, especially when used in conjunction with on-site renewable generation. Conversely, the urban location of Chennai Port presents spatial and operational limitations that support small scale, highly integrated shore power systems as opposed to large centralized ones. The findings demonstrate that grid preparedness should not receive a one-dimensional assessment on the basis of the voltage level and the capacity, but also the area integration and adaptability in operation.

The availability of renewable energy is determinant in the achievement of real decarbonization benefits by shore power. The shift to an annual power-plus arrangement by Deendayal Port and the increasing ability of JNPA to use renewable power allow low-carbon operation of shore power at the system level. On the other hand, the moderate penetration of renewable at Chennai Port reflects a typical issue that urban ports have, i.e. land constraints prevent the use of renewables in large-scale on-site applications. Under these conditions, the off-site purchase of renewable energy or more decarbonization of the grid can become the key to effective shore power decarbonization instead of only local generation. This underlines the need to incorporate shore power planning into greater port and regional energy system transition.

5. Conclusion

This paper suggested a comparative, engineering-based evaluation of green shore power provision at ports on the basis of a limited energy-envelope model based on publicly announced indicators of operation. Through the analysis of the ports that possess different archetypes of operation, the findings indicate that the feasibility of shore power is dictated by the turnaround time of the vessel, vessel type, and vessel frequency of calls but not cargo throughput. Ports that serve containers prefer high-throughput, high-connection shore power systems to support short-duration stays, as opposed to bulk- and tanker-dominated ports which need high-capacity connections that can support long-duration auxiliary loads. Diversified vessel traffic in ports requires flexible and modular shore power configuration to meet heterogeneous energy needs.

The limited energy-cycle approach, presented in the present work, allows to conduct the feasibility analysis in a conservative but informative manner, without the use of proprietary and high resolution vessel load data. This method does not achieve any kind of false accuracy, yet is also strong enough to identify design drivers between port archetypes, so it is most appropriate in the context of early-stage planning and a gradual deployment of shore power infrastructure. The findings also highlight that the electrical infrastructure preparedness and renewable energy presence play a significant role in determining the environmental performance of shore power, where ports that have high grid redundancy or renewable surplus are in a better position to record meaningful emission abatement.

Although the analysis is constrained by the application of literature-based auxiliary power range, qualitative vessel-call intensity, and dynamic operational factors are not used to describe the data, the constraints are indicative of real-world data availability and the study is not an optimization exercise, but a feasibility analysis on the system level. The time-resolved vessel scheduling information, empirical auxiliary load measurements, and techno-economic analysis should be incorporated in future work in order to optimize the system size and investment decisions. Still, the current research offers a clear and replicable framework of the assessment of shore power installation of various ports and is helpful in making the right decision of moving to low-emission shipping.

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