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Emissions of Waiting: Quantifying Avoidable CO2 from Unproductive Berth Time at Tanjung Emas Port, Semarang

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ABSTRACT

Ships emit a disproportionate share of their pollutants while alongside, yet emission abatement at Indonesian ports remains framed principally around fuel quality rather than around the duration for which engines run. This study estimates exhaust emissions from five vessels calling at Tanjung Emas Port, Semarang, using an activity-based bottom-up method in which fuel consumption is derived from engine power, load factor, operating time and specific fuel consumption, and converted to pollutant mass through emission factors for CO, NOx, HC, TSP, SO2 and CO2. Set against published port service time statistics, in which Not Operational Time constitutes 20.03 of 79.89 hours of berthing time, the study estimates that approximately 6.4 tonnes of CO2 per call are emitted during periods in which no cargo work occurs but auxiliary engines continue to run. The study concludes that berth productivity is an emissions variable rather than solely a commercial one, and that scheduling reform offers an abatement pathway available at negligible capital cost and complementary to shore power.

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INTRODUCTION

The background to this study is developed in three steps. First, the scale and health significance of ship exhaust emissions, and their particular concentration within ports, is established. Second, the principal regulatory response to date, which addresses fuel quality rather than fuel quantity, is set out together with the specific gap it leaves open. Third, the operational category this study addresses — emissions arising from unproductive time at berth — is introduced and distinguished from that regulatory gap, leading to the study's objectives.

Maritime transport is the most carbon-efficient mode of freight movement per tonne-kilometre, yet its absolute contribution to atmospheric pollution remains substantial and is concentrated in a manner that magnifies its consequences. Ships burn residual and distillate fuels in engines that emit nitrogen oxides, sulphur oxides, carbon monoxide, hydrocarbons, particulate matter and carbon dioxide, and a disproportionate share of these emissions occurs not at sea but within ports, where vessels operate in close proximity to dense human settlement. Cooper (2003) established early that exhaust emissions from ships at berth constitute a distinct and significant category, and Hulskotte and Denier van der Gon (2010) subsequently quantified fuel consumption and associated emissions at berth through an on-board survey.

The health consequences of this concentration are well documented. Corbett et al. (2007) estimated global mortality attributable to ship emissions, and Viana et al. (2014) assessed the impact of maritime transport upon coastal air quality in Europe. Barregard et al. (2019) quantified the population health burden of Baltic shipping emissions, and Sofiev et al. (2018) demonstrated that cleaner fuels deliver public health benefits, albeit with climate trade-offs. Because port areas in Indonesia frequently adjoin dense urban populations, the exposure pathway is direct.

Regulatory response has focused principally upon fuel quality. The global sulphur cap introduced under MARPOL Annex VI from 2020 reduced permissible sulphur content substantially, and its effects upon air quality and health have been assessed both prospectively and retrospectively (Ji, 2020; Zhao et al., 2026), following earlier evidence from regional fuel switching (Tao et al., 2013). In Indonesia, national regulation likewise establishes ambient air quality standards and emission limits. Fuel quality regulation, however, addresses the composition of what is burned rather than the quantity, and it therefore leaves untouched a category of emission that arises from operational rather than technical causes.

That category is the subject of this study. Where a vessel lies alongside with auxiliary engines running but no cargo work in progress, fuel is consumed and pollutants emitted without any corresponding transport output. Such periods are recorded in port performance statistics as Not Operational Time, and they are ordinarily analysed as a commercial inefficiency, a matter of berth utilisation and vessel turnaround. Their environmental dimension has attracted comparatively little attention, particularly in the Indonesian context, notwithstanding that they represent emissions which could be eliminated by scheduling reform alone, without capital investment or technological change.

This study accordingly estimates exhaust emissions from ships calling at Tanjung Emas Port, Semarang, and identifies where within the port call those emissions arise. Two objectives are pursued: to estimate the quantity of exhaust emissions produced by vessels during a port call, disaggregated by operational phase and by engine; and to identify the phase in which emissions are highest and to quantify the portion attributable to unproductive time. The contribution lies in connecting an emission inventory to port service time statistics, thereby rendering visible an abatement opportunity that neither literature alone discloses.

THEORETICAL REVIEW

Methods of Ship Emission Estimation

Two broad approaches to estimating ship emissions have developed. Top-down methods apportion aggregate fuel sales to activities, while bottom-up or activity-based methods build the estimate from vessel movements, engine characteristics, and operating profiles. Miola and Ciuffo (2011) compared the available modelling approaches and data sources through meta-analysis, and Moreno-Gutierrez et al. (2015) conducted a comparative analysis of current methods for estimating shipping emissions and energy consumption. Nunes et al. (2017) reviewed the activity-based methodology specifically, establishing the parameter requirements and the principal sources of uncertainty.

The activity-based approach has become dominant, in part because Automatic Identification System data supply the vessel movement information it requires. Jalkanen et al. (2009) developed a modelling system for marine traffic exhaust emissions applied to the Baltic, subsequently extended to particulate matter and carbon monoxide (Jalkanen et al., 2012). Goldsworthy and Goldsworthy (2015) modelled engine exhaust emissions in ports and coastal waters from terrestrial AIS data, and comparable inventories have since been constructed for numerous ports, including Tianjin (Chen et al., 2016), Qingdao (Chen et al., 2017), Incheon using vessel traffic service data (Lee et al., 2021), and Busan (Woo & Im, 2021). Cammin et al. (2023) proposed tiered prediction models permitting inventories to be constructed at varying levels of data availability.

Where AIS or vessel traffic service data are unavailable, estimation proceeds from vessel particulars and recorded operating times, as in the present study. Saracoglu et al. (2013) applied such an approach at Izmir, and Iodice et al. (2017) assessed emissions in manoeuvring mode and under fuel switching numerically. The method's accuracy depends upon the fidelity of the assumed load factors and emission factors, a limitation addressed below.

Emissions at Berth

The concentration of emissions in the alongside phase is a consistent finding. Cooper (2003) documented the magnitude of at-berth emissions, and Hulskotte and Denier van der Gon (2010) derived fuel consumption at berth from direct survey rather than assumption, providing an empirical basis for auxiliary engine load estimates. Lonati et al. (2010) assessed the air quality impact of at-berth emissions in the context of a proposed freight port, and Toscano and Murena (2019) reviewed atmospheric ship emissions in ports and their correlation with traffic data.

Port-city studies have quantified the resulting exposure. Tichavska and Tovar (2015) developed a port-city exhaust emission model applied to cruise and ferry operations at Las Palmas, Merico et al. (2017) compared approaches across four Adriatic-Ionian port cities, and Murena et al. (2018) assessed the air quality impact of cruise ship emissions at Naples. Papaefthimiou et al. (2016) evaluated cruise ship emissions across Greek ports, and De Melo Rodriguez et al. (2017) developed indicators for cruise vessel emissions at ports. Of particular relevance to the present study, Nguyen et al. (2022) examined emissions in the hotelling phase and during loading and unloading specifically at Southeast Asian ports, and Nguyen (2025) subsequently estimated the associated social costs at Southeast Asian container ports.

Abatement: Shore Power and Operational Measures

The principal technological remedy for at-berth emissions is the supply of shore-side electricity, permitting auxiliary engines to be shut down while alongside. Zis (2019) assessed the prospects of cold ironing as an emission reduction option, and Dai et al. (2019) conducted an environmental and techno-economic analysis of shore side electricity. Piccoli et al. (2021) examined the environmental and regulatory dimensions of cold ironing planning for an Adriatic route, and Le (2024) analysed the drivers of and barriers to implementation. Innes and Monios (2018) identified the particular challenges facing small and medium ports, which lack the call volumes over which the substantial capital cost of shore power installations can be amortised.

Operational measures constitute an alternative pathway requiring little capital. Du et al. (2011) formulated berth allocation with explicit consideration of fuel consumption and vessel emissions, establishing that scheduling decisions carry emission consequences. Berechman and Tseng (2012) estimated the environmental costs of port-related emissions at Kaohsiung, and Rauca et al. (2025) examined the influence of port performance upon vessel operating costs and emissions jointly. Liu et al. (2025) analysed carbon emission dynamics under in-port congestion using a data-driven approach. These studies establish in principle the link between port productivity and emissions; the present study quantifies it for a specific Indonesian port. Recent evidence corroborates this operational pathway at a different point in the supply chain: Rhodes et al. (2025) found that a coordinated port queuing system reduced container-shipping CO2 emissions by making waiting time itself, rather than propulsion, the lever of adjustment, a finding that parallels the present study's focus on waiting-related berth emissions, albeit at the offshore rather than the alongside stage of the port call.

Green Port Policy

Port decarbonisation has developed into a substantial policy field. Karagkouni and Boile (2024) classified the green practices implemented across ports, encompassing technologies, tools and strategies. Zhang et al. (2024)

reviewed systematically the routes to comprehensive carbon emission reduction in ports, and Song (2024) surveyed seaport decarbonisation measures and the roadmap to net zero. Within the Indonesian context, Winarno et al. (2024) analysed emissions arising from port activity at Tanjung Perak, Surabaya, using system dynamics with attention to berthing duration, which constitutes the closest national analogue to the present study.

Research Gap

Three gaps emerge. First, ship emission inventories are overwhelmingly constructed for large ports in Europe, East Asia and North America, with Indonesian ports underrepresented notwithstanding the country's archipelagic dependence upon sea transport. Second, the literature treats emissions at berth as a function of berthing duration in aggregate, without distinguishing productive from unproductive time within that duration. Third, the port efficiency and port emissions literatures have developed largely in parallel, so that the emission consequences of the specific operational failures documented in the productivity literature remain unquantified. This study addresses all three.

METHODOLOGY

Approach and Setting

The study employed an activity-based bottom-up estimation applied to five vessels calling at Tanjung Emas Port, Semarang. The vessels comprised one general cargo ship, two chemical tankers, and two container ships, a composition reflecting the mixed traffic the port receives. Data were obtained from vessel service records, port facility documentation, and vessel particulars for the calls examined, supplemented by observation of operations.

Estimation Procedure

Estimation proceeded in three stages. First, specific fuel consumption was determined for the main engine and the auxiliary engine of each vessel, expressed in litres and kilograms per hour, from engine rating and manufacturer data. Second, fuel consumption for each operational phase was computed as the product of specific fuel consumption, the engine load factor appropriate to that phase, and the recorded duration of the phase. Four phases were distinguished: dead slow, slow, and half ahead, corresponding to manoeuvring within the port, and cargo operations, corresponding to the period alongside. Third, pollutant masses were obtained by multiplying fuel volume by emission factors for each species.

The emission factors applied were 43.5 g/L for carbon monoxide, 11 g/L for nitrogen oxides, 26 g/L for hydrocarbons, 2.4 g/L for total suspended particulates, 19 g/L for sulphur dioxide, and 3,150 g/L for carbon dioxide. These factors express emissions as direct engine output without abatement, since none of the vessels examined was fitted with exhaust after-treatment. Estimates were computed separately for main and auxiliary engines, permitting the contribution of each to be distinguished, and separately for each phase, permitting the distribution across the port call to be established.

Linking Emissions to Port Service Time

To establish the portion of alongside emissions attributable to unproductive periods, the hourly emission estimates were combined with port service time statistics for Tanjung Emas. These statistics decompose the Turn Round Time of 105.21 hours per vessel into a Berthing Time of 79.89 hours, which is itself decomposed into Effective Time of 59.60 hours, Idle Time of 0.28 hours, and Not Operational Time of 20.03 hours. Not Operational Time denotes periods during which the vessel occupies the berth but no cargo work proceeds, arising from unavailability of handling equipment or of dockworker labour. Because auxiliary engines continue to operate throughout this period, supplying power for on-board cargo gear and accommodation, the emissions associated with it were computed as the product of Not Operational Time and mean auxiliary hourly emissions.

Limitations of the Method

Three limitations of the estimation method are stated at the outset. First, emission factors are generic rather than engine-specific, and actual emissions vary with engine condition, load, and fuel composition; the estimates are therefore indicative rather than measured. Second, the sample comprises five vessels observed over single calls, which cannot represent the full distribution of the port's traffic. Third, the port service time statistics are drawn from published operational reporting for the port as a whole rather than from the five calls examined, so the linkage between the two datasets is at the level of the port rather than the individual vessel.

RESULTS

Fuel Consumption and Emissions by Phase

Estimated carbon dioxide emissions by operational phase for the three vessels with complete phase records are reported in Table 1 and displayed in panel (a) of Figure 1.

Table 1. Estimated CO2 emissions by operational phase (tonnes per port call).

Vessel	Type	Manoeuvring CO2 (t)	Alongside CO2 (t)	Total CO2 (t)	Alongside share (%)
MV Salindo Perdana I	General cargo	0.463	3.316	3.779	87.7
MT Trihasta I	Chemical tanker	0.307	3.104	3.411	91.0
MT Blue Sky	Chemical tanker	0.300	2.258	2.558	88.3
Mean	-	0.357	2.893	3.249	89.0

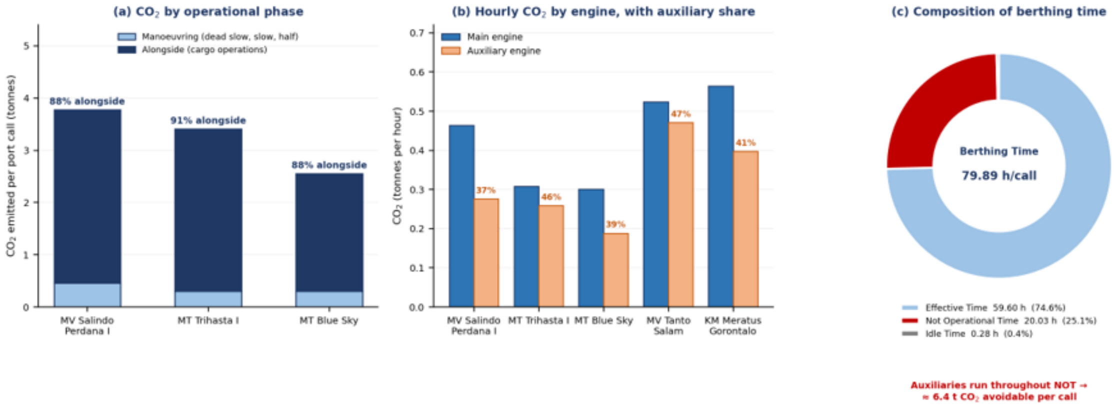

Figure 1. CO2 by operational phase, hourly CO2 by engine, and the composition of berthing time.

The distribution is pronounced and consistent. MV Salindo Perdana I emitted 3.316 of 3.779 tonnes of carbon dioxide while alongside, equivalent to 87.7% of the total for the call. MT Trihasta I emitted 3.104 of 3.411 tonnes alongside, or 91.0%, and MT Blue Sky 2.258 of 2.558 tonnes, or 88.3%. The mean across the three vessels is 89.0%. Manoeuvring, notwithstanding the higher engine loads it involves, contributes little because its duration is short: the combined dead slow, slow and half ahead phases occupied approximately one hour per call, against twelve hours of cargo operations.

Contribution of Auxiliary Engines

Hourly emissions disaggregated by engine are reported in Table 2 and displayed in panel (b) of Figure 1.

Table 2. Estimated hourly emissions by engine (tonnes per hour).

Vessel	Main engine CO2 (t/h)	Auxiliary CO2 (t/h)	Total (t/h)	Auxiliary share (%)
MV Salindo Perdana I	0.463	0.276	0.739	37
MT Trihasta I	0.307	0.259	0.566	46
MT Blue Sky	0.300	0.188	0.488	39
MV Tanto Salam	0.523	0.470	0.993	47
KM Meratus Gorontalo	0.563	0.397	0.960	41
Mean	0.431	0.318	0.749	42

Auxiliary engines contribute between 37% and 47% of hourly carbon dioxide across the five vessels, with a mean of 0.318 tonnes per hour. The share is highest for the container vessels, at 47% for MV Tanto Salam and 41% for KM

Meratus Gorontalo, reflecting the electrical demand of on-board cargo handling gear. The magnitude of this contribution is material: for a vessel alongside for twelve hours, auxiliary engines alone account for approximately 3.8 tonnes of carbon dioxide.

Emissions Attributable to Unproductive Time

The composition of berthing time at Tanjung Emas is displayed in panel (c) of Figure 1 and reported in Table 3. Of 79.89 hours of Berthing Time per vessel, 59.60 hours or 74.6% constitute Effective Time, 0.28 hours or 0.4% Idle Time, and 20.03 hours or 25.1% Not Operational Time.

Table 3. Decomposition of port service time and associated avoidable emissions.

Component of port service time	**Duration (hours per call)**	**Share of berthing time (%)**	**Emission implication**
Turn Round Time	105.21	-	Total time in port
Berthing Time	79.89	100.0	Period alongside; auxiliaries running
Effective Time	59.60	74.6	Productive cargo work
Idle Time	0.28	0.4	Negligible
Not Operational Time	20.03	25.1	No cargo work; auxiliaries still running
Avoidable CO2 per call	-	-	20.03 h x 0.318 t/h = approximately 6.4 t

Applying the mean auxiliary emission rate of 0.318 tonnes of carbon dioxide per hour to the 20.03 hours of Not Operational Time yields an estimate of approximately 6.4 tonnes of carbon dioxide per port call emitted during periods in which the vessel occupies a berth but no cargo work proceeds. Observation confirmed the mechanism: auxiliary engines are started when the vessel makes fast and continue to run while cargo operations await the availability of shore handling equipment and dockworker labour, so that a period recorded as commercially unproductive is nonetheless fully productive of emissions.

DISCUSSION

The Location of Emissions Within the Port Call

The finding that 89% of carbon dioxide is emitted alongside rather than during manoeuvring confirms in the Indonesian context a pattern established elsewhere. Cooper (2003) and Hulskotte and Denier van der Gon (2010) documented the significance of at-berth emissions in European settings, and Nguyen et al. (2022) established the pattern for the hotelling and cargo phases at

Southeast Asian ports specifically. The consistency is unsurprising given the underlying arithmetic: manoeuvring involves high engine loads but occupies approximately one hour, whereas cargo operations involve lower loads but occupy twelve. This finding is directionally consistent with the at-berth dominance documented in European and East Asian ports (e.g., Cooper, 2003; Hulskotte & Denier van der Gon, 2010; Nguyen et al., 2022), but no prior Indonesian inventory disaggregates ship emissions by operational phase, so whether the specific share reported here reflects a genuinely more constrained cargo-handling environment at Tanjung Emas, or simply the absence of a prior national benchmark against which to judge it, cannot yet be resolved.

The practical consequence is that abatement effort directed at manoeuvring, such as tug assistance optimisation or approach speed management, addresses a small fraction of the total. Measures addressing the alongside phase, whether by substituting shore electricity for auxiliary generation or by shortening the phase itself, address the overwhelming majority. This ordering is not evident from aggregate port emission totals and emerges only when the inventory is disaggregated by phase.

Unproductive Time as an Emissions Category

The central contribution of this study is the identification of unproductive berth time as a distinct emissions category. Approximately 6.4 tonnes of carbon dioxide per call are emitted during periods in which no cargo work occurs. These emissions are avoidable in a specific and demanding sense: their elimination requires neither new technology nor capital investment nor regulatory change, but only that cargo handling equipment and labour be available when the vessel is. They arise from a coordination failure rather than from a technical constraint.

This connects two literatures that have developed separately. The port productivity literature treats Not Operational Time as a commercial loss, measured in berth occupancy and vessel turnaround, and the same operational failures, namely equipment unavailability and labour scheduling, have been documented as principal constraints at Indonesian multipurpose ports. The port emissions literature treats berthing duration as an input to inventory calculation without distinguishing its productive from its unproductive components. Du et al. (2011) established that berth allocation carries emission consequences, and Rauca et al. (2025) examined port performance and emissions jointly, but the specific quantification of emissions attributable to unproductive time within berthing has not to our knowledge been performed for an Indonesian port. Liu et al. (2025) approached the question from the congestion side. This differs methodologically from Winarno et al.'s (2024) system-dynamics analysis of Tanjung Perak, which treated berthing duration as an aggregate driver of port emissions: the present decomposition into effective, idle and not-operational components isolates the avoidable share specifically, a distinction Winarno et al.'s aggregate treatment does not draw, and one that also goes beyond the offshore-queuing focus of Rhodes et al. (2025) by locating the avoidable emission at the berth itself rather than before arrival.

The implication for policy is that berth productivity is an environmental instrument. An operator who reduces Not Operational Time from 20.03 to 10 hours per call halves the associated emissions, achieving an abatement of approximately 3.2 tonnes of carbon dioxide per call at no capital cost. Across a port handling a thousand calls annually this amounts to some 3,200 tonnes. Framed in these terms, investment in cargo handling equipment reliability and in dockworker scheduling acquires an environmental justification additional to its commercial one.

Relation to Shore Power

Shore-side electricity remains the principal technological remedy for at-berth emissions, and the auxiliary engine contribution documented here, at 37% to 47% of hourly carbon dioxide, indicates the scale of what it could displace. Zis (2019) and Dai et al. (2019) assessed its emission and economic performance, and Piccoli et al. (2021) its regulatory dimension. Innes and Monios (2018), however, identified the difficulty confronting small and medium ports, where call volumes are insufficient to amortise the substantial capital cost, and Le (2024) catalogued the wider barriers to implementation.

The two pathways are complementary rather than alternative, and their sequencing matters. Reducing unproductive time lowers emissions immediately and at negligible cost, and it simultaneously improves the economics of any subsequent shore power installation by raising berth throughput. Conversely, installing shore power without addressing unproductive time would eliminate the emissions but preserve the underlying inefficiency, and would require the connection to be maintained through hours in which no work proceeds. Operational reform is therefore the logical first step, with electrification following where call volumes justify it.

Health and Regulatory Context

The species estimated here include pollutants of direct health consequence as well as carbon dioxide. Corbett et al. (2007) established global mortality attributable to ship emissions, Viana et al. (2014) documented the coastal air quality impact in Europe, and Barregard et al. (2019) quantified the population health burden in the Baltic. Because Tanjung Emas adjoins the urban area of Semarang, emissions of nitrogen oxides and particulates during extended alongside periods reach a populated receptor directly, and their reduction carries a local health benefit additional to the climate benefit of reduced carbon dioxide.

Regulation has concentrated upon fuel quality, through the global sulphur cap and its national equivalents (Ji, 2020; Zhao et al., 2026; Tao et al., 2013). Such measures reduce the sulphur and particulate content of a given quantity of fuel burned but do not reduce the quantity. The abatement identified here is complementary in precisely this respect: it reduces the fuel burned rather than its composition, and it therefore acts upon carbon dioxide, which fuel quality regulation does not address. Within the broader green port agenda (Karagkouni & Boile, 2024; Zhang et al., 2024; Song, 2024), operational efficiency measures of this kind occupy the position of lowest cost and most immediate availability.

Limitations

Five limitations qualify these findings. First, emission factors are generic rather than measured for the specific engines, and actual emissions vary with engine condition, load and fuel sulphur content; the estimates are indicative. Second, the sample of five vessels over single calls cannot represent the distribution of the port's traffic, and the three vessels with complete phase data are fewer still. Third, the port service time statistics used to derive the avoidable emission estimate are port-wide and drawn from operational reporting for an earlier period, so the linkage to the five calls is indirect and the estimate should be regarded as illustrative of magnitude rather than precise. Fourth, auxiliary load during Not Operational Time was assumed equal to the mean alongside rate, whereas load may in fact be lower when cargo gear is not operating, which would render the estimate conservative in one direction and overstated in another. Fifth, no dispersion modelling was undertaken, so the estimates describe emissions rather than ambient concentrations or exposure.

CONCLUSIONS AND RECOMMENDATIONS

The central finding of this study is that ship emissions at Tanjung Emas Port are concentrated overwhelmingly at berth rather than during manoeuvring, and that a specific, avoidable share of that berth emission — arising from unproductive time rather than cargo work — can be isolated and quantified.

This study estimated exhaust emissions from five vessels calling at Tanjung Emas Port using an activity-based bottom-up method, disaggregated by operational phase and by engine. A mean of 89.0% of carbon dioxide was emitted while alongside rather than during manoeuvring, and auxiliary engines accounted for between 37% and 47% of hourly carbon dioxide, with a mean of 0.318 tonnes per hour. Setting these rates against port service time statistics, in which Not Operational Time constitutes 20.03 of 79.89 hours of berthing time, the study estimates approximately 6.4 tonnes of carbon dioxide per call emitted during periods in which the vessel occupies a berth but no cargo work proceeds.

Four recommendations follow. First, the port operator should treat berth productivity as an environmental performance indicator alongside its established commercial function, and should report Not Operational Time with its emission equivalent. Second, the operational causes of Not Operational Time, principally the availability and reliability of cargo handling equipment and the scheduling of dockworker labour, should be addressed as the abatement measure available at lowest cost and shortest lead time. Third, shore-side electricity should be evaluated for berths receiving vessels with high auxiliary loads, particularly container vessels, but should be sequenced after operational reform so that the installation serves productive rather than unproductive hours. Fourth, emission estimation should be institutionalised as a routine reporting function rather than conducted as an occasional study, so that the effect of interventions can be observed.

FURTHER STUDY

Four directions for further work are indicated. First, the inventory should be extended to the full annual traffic of the port using Automatic Identification System data, following the approach of Goldsworthy and Goldsworthy (2015) and Woo and Im (2021), which would replace the present five-vessel sample with a complete account. Second, auxiliary engine load during Not Operational Time should be measured rather than assumed, since the avoidable emission estimate is directly proportional to it. Third, dispersion modelling should be undertaken to translate emissions into ambient concentrations at populated receptors in Semarang, permitting the health benefit of abatement to be estimated in the manner of Lonati et al. (2010) and Murena et al. (2018). Fourth, a techno-economic comparison of operational reform against shore power investment for this port would establish the marginal abatement cost of each and the sequence in which they should be pursued.

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