Environmental and health consequences of shore power for vessels calling at major ports in India

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Abstract

To reduce local air pollution, many ports in developed countries require berthed ships to use shore-based electricity instead of burning diesel to meet their electricity requirement for loads such as lights, cargo-handling equipment, and air conditioning. The benefits of this strategy in developing countries remain understudied. Based on government data for all major ports in India, we find that switching from high-sulfur fuel to shore power reduces hoteling emissions of particulate matter (PM$_{2.5}$) by 88%; SO$_2$ by 39%; NO$_x$ by 85%; but increases CO$_2$ emissions by 12%. Switching from low-sulfur fuel reduces hoteling emissions of PM$_{2.5}$ by 46% and NO$_x$ by 84% but increases SO$_2$ emissions by 240% and CO$_2$ emissions by 17%. The lifetime cost savings from the switch to electricity are $73$ M for high-sulfur fuel and $370$ M for low-sulfur fuel. We estimate that switching from high-sulfur fuel to shore power might avoid at most a couple of dozen premature deaths each year, whereas switching from low-sulfur fuel could lead to a slight increase in premature mortality. Therefore, policymakers must first clean up power generation for shore power to be a viable strategy to improve air quality in Indian port cities.

1. Introduction

The electrification of applications that currently involve the combustion of fossil fuels has been widely promoted as a strategy to achieve decarbonization and to reduce local air pollution (Roberts 2017, Davis et al 2018). However, the effectiveness of this strategy depends on the local electricity generation mix over the lifetime of the product or infrastructure that is electrified. Indeed, scholars have raised grave concerns about the conventional wisdom that electrification by itself produces an environmental benefit. For example, in much of the eastern United States, electric vehicles do more damage to human health and the environment than do gas-electric hybrids (Holland et al 2016, 2019). In this analysis, we ask whether the benefits of electrification exceed the costs in a sector and context that has drawn relatively little attention: ocean shipping in India.

The combustion of shipping fuels emits criteria pollutants such as fine particulate matter (PM$_{2.5}$), oxides of nitrogen (NO$_x$), sulfur dioxide (SO$_2$) (Endresen 2003, Dalsøren et al 2009, Eyring et al 2010, Liu et al 2016), that damage the environment (Endresen 2003, I-m et al 2013), and human health (Corbett et al 2007, Sofiev et al 2018). Criteria pollutants from ships caused ∼60 000 premature deaths world-wide in 2015 (International Council on Clean Transportation 2019). That number is expected to increase to ∼250 000 premature deaths in 2020 (Sofiev et al 2018). Global shipping accounted for 2.6% of the global carbon dioxide (CO$_2$) emissions in 2012 (Smith et al 2014). If left unregulated, CO$_2$ emissions from international shipping are expected to grow between 50% and 250% by 2050 (Smith et al 2014). While electrified ocean shipping remains elusive, there is great interest in the electrification of various port operations, (Kim et al 2012, Iris and Lam 2019, Edison Electric Institute 2020) and in the electrification of a ship’s operations when it is in port (Hall 2010, International Council on Clean Transportation 2015, Vaishnav et al 2016, Winkel et al 2018).
The second strategy has been shown to produce a net benefit in many ports in the United States and Europe to the extent that some ports have started to mandate it (California Air Resources Board 2020b). In this paper, we test a hypothesis that would seem to follow logically from these findings: given that ships that berth at Indian ports are allowed to burn far dirtier fuel than ships in Europe and North America are, and given that Indian cities are far more densely populated than those in Europe and North America, the electrification of a ship’s operations in port might be expected to produce a large benefit. Indeed, the logic of this hypothesis is so compelling that the Government of India (GoI) has begun to invest in the provision of electricity to ships in port (Government of India 2020). Our results suggest that this strategy is unlikely to be of much value for cargo vessels docked in major Indian ports until such time as the electricity generation that provides shore power is outfitted with much better pollution controls.

The International Maritime Organization (IMO) regulates pollution from ocean shipping. IMO’s revised Maritime Agreement Regarding Oil Pollution Annex VI, effective from 1 January 2020 (see supplementary information S1.1 (available online at stacks.iop.org/ERL/16/064042/mmedia)) seeks to reduce sulfur dioxide (SO$_2$) emissions from ocean shipping. Before this regulation came into effect, ships could burn fuel with up to 3.5% sulfur. Under this regulation, ocean-going vessels (OGVs) are permitted to use fuel with up to 0.5% sulfur (5000 ppm) outside the emission control areas (ECAs). The IMO has designated four ECAs (the North Sea, the Baltic Sea, the US Caribbean, and the coastal waters of Canada and the US), where permissible sulfur content of the fuel being used is 0.1% sulfur (1000 ppm) (Wan et al 2016). India is not a part of an IMO ECA and hence ships at the Indian coast burn 0.5% sulfur fuel.

Asia had the largest share (UNCTAD 2019a) of world seaborne trade in 2018 with the continent accounting for 41% of total loaded and 61% of total unloaded goods (UNCTAD 2019b). Emissions from seaborne trade in East Asia have been estimated to result in between 14 500 and 37 500 premature deaths globally each year (Liu et al 2016). To address this, countries such as China have capped sulfur content in marine fuels to 0.5% sulfur (5000 ppm) by designating domestic emission control areas (DECA$s$) across its national coastline and installing shore power at Chinese ports. In 2020, 493 berths in Chinese ports are expected to be equipped with shore power infrastructure (Natural Resources Defense Council 2019).

Similar steps are being taken by the GoI to curtail air pollution. Beginning in 2020, new regulations tightened the standard for the sulfur content of on-road diesel from 350 ppm (International Council on Clean Transportation 2012) to 10 ppm (International Council on Clean Transportation 2016). Also, ocean freight through Indian ports is expected to grow at 18% per annum (Assocham 2017, Government of India 2017) and GoI is building shore power infrastructure at Indian ports as part of their ‘Green Ports Initiative’ (Bankes-Hughes 2018). There are Indian ports such as the V.O. Chidambararan (VOC) Port in Tamil Nadu (southern India) that already use shore power (Maritime Executive 2017). Finally, the cities adjacent to India’s ports are more densely populated than those in Europe and North America. For example, Mumbai has a population density of 31 000 km$^{-2}$ and Gandhidham, which adjoins India’s largest major port (Deendayal Port), has a population density of <3000 km$^{-2}$ (World Population Review 2019). For all these reasons, we anticipate that because the relative share of local SO$_2$ emissions from shipping in Indian port cities is likely to increase, shore power could potentially benefit air quality at major ports in India. Despite these developments, we are not aware of a rigorous environmental benefit-cost analysis of shore power in India. Literature on shipping impacts for India is sparse, presumably because of a lack of public data on Indian ports. Our study fills this gap.

In this analysis, we explore the potential of shore power as a strategy for India’s 12 major ports. We assume an electricity system where the dominant source of load-following electricity is coal over the entire lifetime of any vessel that is switched to shore power. We report the results for 2017, the base year of the analysis when there is virtually no post-combustion scrubbing of emissions from coal-fired power plants. We also repeat the analysis for 2030 and assume that by then the emissions intensity of coal-fired plants is substantially reduced through the installation of air pollution control technology. In each case, we assume that the system remains static over the period of the analysis. Furthermore, we (a) quantify the annual emissions of ships berthed at major ports in India in 2017–2018, (b) assess the contribution of berthed ship emissions as a proportion of total emissions in cities near major ports, (c) develop bottom-up hourly emission inventories for all major ports on the basis of vessel activity and fuel consumption calculations and use those results to estimate the change in emissions that would be achieved if ships were instead supplied with electricity generated on the shore, (d) estimate the change in vessel operator’s fuel costs if they were to switch to shore power instead of burning marine gas oil (MGO, 0.5% S), or residual oil (RO, 2.7% S) for meeting their load requirement, (e) estimate the net health and environmental consequences of switching to shore power in port cities. We assess these questions under two fuel use scenarios: first, assuming that ships burn lower-sulfur MGO to generate electricity, as required by international law from 1 January 2020 onwards, and
shows the 12 major ports in India which are governed by the Ministry of Shipping (MoS) through respective Port Trusts (geographic details in supplementary information S2.1) (Ministry of Shipping Government of India 2019). These are the ports primarily visited by the large cargo vessels that are the focus of this paper. They handled ~680 million tonnes of cargo from April 2017 to March 2018 (Indian Ports Association 2018). By comparison, the Port of Los Angeles (POLA) handled ~195 million metric revenue tonnes of cargo from July 2017 to June 2018 (Port of Los Angeles 2019).

In addition to the major ports, there are over 200 non-major ports, many of which are not equipped to handle large cargo vessels. Many fishing vessels call at small and unofficial ports, and undoubtedly contribute to pollution near these ports. However, it is not clear that they produce a significant amount of electricity for hoteling loads, or that they could be profitably switched to shore power. As explained in supplementary information S2.1, since the focus of our analysis is on reducing pollution by switching to shore power at berths, all vessel calls were considered.

We are aware of two studies that systematically assessed emissions from ships in major ports in India. The first study by Joseph et al (2009) relies on assumptions from the late 1990s for estimating auxiliary engine load factors. The analysis was conducted for the Jawaharlal Nehru Port (JNPT) for the year 2006 and the authors determine the emissions contribution of total suspended particulate (TSP) matter, respirable particulate matter (PM$_{10}$), SO$_2$ for different port activities (port operations, construction, road transport) and find that TSP contributions dominated accounting for 68.5% of the total pollutant load and the minimum contribution was from SO$_2$ (5.3%). The paper found that maximum NO$_x$ was emitted by the road transport sector and maximum SO$_2$ emissions in the port were from the maritime sector. The second study looked at emissions during 2013–2014 in the port of Kolkata (eastern coast of India) (Mandal et al 2017). The authors estimated annual emissions for Kolkata port for NO$_x$, SO$_2$, PM$_{10}$, PM$_{2.5}$, carbon monoxide (CO), hydrocarbons (HC) and CO$_2$ during ships’ different activity modes (reduced speed zone, maneuvering and hoteling) and found NO$_x$, SO$_2$ emissions to be the dominant among pollutant species. The authors attributed the high emissions to the longer length of the shipping channel, use of bunker fuel, non-compliance of vessels with IMO’s emission standards and long turnaround time at berth. The study is limited in that the authors studied the emissions only at this one port for 2013–2014. Kolkata Port’s shipping activity increased by ∼35% (Indian Ports Association 2019) between 2013 and 2017 and the emissions at the port are likely higher than what is reported in the paper. Finally, there are two big facilities under the jurisdiction of the Kolkata Port Trust, namely, (a) Kolkata Docking System (KDS) and, (b) Haldia Dock Complex (HDC), (located about 104 km away from KDS). Mandal et al (2017) appears not to have included HDC, which may also have resulted in an underestimate of emissions. In our analysis, we have estimated emissions at both KDS and HDC.

2. Prior work

Many studies have shown that, in North America, Europe and Asia, the environmental and health benefits of shore power exceed the costs. Vaishnav and colleagues conducted a study on US ports and calculated an estimated social benefit of $70–$150 million per year by retrofitting one-fourth to two-thirds of all vessel calling at US ports (Vaishnav et al 2016). Winkel et al quantified the economic and environmental benefits of shore power in Europe while accounting for barriers in its implementation (Winkel et al 2016). The health benefits of shore power in the study were estimated to be €2.63 billion and €2.93 billion for 2010 and 2020 respectively (Winkel et al 2016). In 2010, a UK study estimated that using shore power reduced the emissions from berthed vessels by 91.6% for NO$_x$, 75.6% for CO$_2$, 45.8% for SO$_2$, and 24.5% for CO$_x$ (Hall 2010). The authors of the study also looked at the potential of shore power to reduce at-berth CO$_2$ emissions across countries and found it to be most effective in Norway (99.5% reduction), France (85% reduction), Japan (35.8% reduction), UK (24.5% reduction), and Italy (27.3% reduction) (Hall 2010). Wang et al found that the adoption of shore power at the port of Shenzhen in 2020 would reduce SO$_2$ by 88%, NO$_x$ by 94%, PM by 95% and CO$_2$ by 37%, but it seems to be a more expensive strategy compared to fuel switching (International Council on Clean Transportation 2015). If 80% of the container ships docking at the port of Shenzhen were to use shore power in 2020, then the per-tonne costs of reducing NO$_x$, PM, SO$_2$, and CO$_2$ were estimated to be $56 K, $1.4 M, $290 K and $2300 respectively (International Council on Clean Transportation 2015). While recent shipping studies in Asia focus on East Asia (Corbett 2016, Liu et al 2016) and China, (Fu et al 2017, Zhang et al 2017, Liu et al 2018), very few studies (Joseph et al 2009, Mandal et al 2017) address the problem of air pollution from ocean shipping in India.

We are aware of two studies that systematically assessed emissions from ships in major ports in India. The first study by Joseph et al (2009) relies on assumptions from the late 1990s for estimating auxiliary engine load factors. The analysis was conducted for the Jawaharlal Nehru Port (JNPT) for the year 2006 and the authors determine the emissions contribution of total suspended particulate (TSP) matter, respirable particulate matter (PM$_{10}$), SO$_2$ for different
power at major ports, small fishing vessels and non-major ports are not included in the analysis.

3.2. Vessel call information

Through correspondence and meetings with stakeholders at various levels in the MoS, GoI, Port Trusts, Indian Ports Association, the Indian Coast Guard and the Indian Army, we obtained vessel activity data for all 12 major ports in India. Our vessel call dataset consists of detailed information on ships, including each ship’s IMO registration number, Maritime Mobile Service Identity (MMSI), a unique nine-digit number which identifies each ship’s Automatic Identification System station, Vessel Name, Vessel Type, Deadweight Tonnage (DWT), Gross Register Tonnage (GRT), Flag, Cargo information (for some ports), pilotage time, berth arrival and berth departure time.

These data are all for the same one year time window: March 2017–March 2018. In the raw data, there were some vessel calls at ports for which the IMO registration number and MMSI information was missing. To obtain this information from online data at MarineTraffic, we developed a web scraper in the Python programming language to find the vessel IMO number, MMSI number, vessel age, and vessel type based on vessel name, GRT and DWT. In our analysis, we consider only vessels that remain in port for longer than 5 h, and less than 230 h, which is the 98th percentile of the durations of all port calls. These vessels are in port for a sufficient time to be connected to shore power; the upper limit excludes vessels that may be in port, but not active. The details of how we processed the raw data obtained from port authorities for analysis are in supplementary information S2.2.

3.3. Emissions calculation

The emissions for OGVs for each vessel call were estimated according to the following equation:

\[ E_{i,j} = EF_i \times A_j \times t_j \]

where:

- \( E_{i,j} \) = Total emissions, in tonnes, for pollutant \( i \) (PM\(_{2.5}\), SO\(_2\), NO\(_x\), and CO\(_2\)) for vessel call \( j \)
- \( EF_i \) = Emission factor for pollutant \( i \) expressed in g (kWh)**−1** of electricity generated by the auxiliary engine
- \( A_j \) = Auxiliary engine's actual operating load for vessel call \( j \) (in kW) based on the vessel type and its size
- \( t_j \) = the time (in hours) the vessel spent hoteling during vessel call \( j \)

The emission factors for PM\(_{2.5}\), NO\(_x\), SO\(_2\), and CO\(_2\) were obtained from the U.S. Environmental Protection Agency (EPA) guidelines for compiling mobile emissions inventories (EPA 2009). A similar approach was used by Mandal et al. (2017) and Joseph et al. (2009).

The total time spent by a vessel hoteling at the port was determined by subtracting berth arrival time from the berth departure time in our datasets. Finally, we multiplied the emission factors by estimates of the hoteling load (expressed in kWh) for different vessel types and sizes to get emissions of respective vessel calls. While we calculated emissions for each vessel call, the results reported below are aggregated by vessel, vessel type, and as annual totals. The emission calculations were performed both for RO and MGO.

3.4. Auxiliary engine power

The auxiliary hoteling loads were estimated by multiplying the total berthing time (in hours) and the auxiliary engine load under operation (in kW) of the vessel of a given type and size. Our calculation is based on the approximation that the auxiliary hoteling load of a vessel scales linearly with its capacity in deadweight tonnes. In addition to using Goldsworthy et al. (2019) auxiliary engine load estimates, we compared the vessel sizes and ages in our dataset, against those that called at POLA and Port of Long Beach (POLB) (see supplementary figure 3). We found that...
the vessels in our dataset are of a comparable vintage to the ones in those ports. As such, we assumed that applying the relationship between vessel size and auxiliary loads observed in POLA (Starcrest Consulting Group 2017b) and POLB’s (Starcrest Consulting Group 2017a) 2017 emissions inventory is appropriate (see supplementary information S2.3).

3.5. India’s state grid emission factors
We assumed that a vessel would require at maximum the same amount of electricity from shore power as it gets from running its on-board generator. The World Bank reports transmission and distribution (T&D) losses for India as ∼19% (World Bank 2018), including theft (Nirula 2019). The actual technical losses are unknown. We assume T&D losses to be 10%. Coal contributed ∼76% to aggregate electricity generation in India during 2017–2018 (Central Electricity Authority 2018a). In our analysis, we assume that 76% of India’s electricity in 2017 came from coal based electric power generation, but all of its load-following electricity—which is what is relevant to the discussion of shore power—comes from coal. Besides coal, gas generates ∼4%; the rest is generated by non-emitting sources (Central Electricity Authority 2018a). We neglect air emissions from natural gas-fired power generation. Since all other sources of power used in India produce no emissions from combustion, we assume that all power sector emissions come from the combustion of coal.

For shore based electricity, we use the dataset from Oberschelp et al (2019), which provides annual coal based PM$_{2.5}$, SO$_2$, NO$_x$, and CO$_2$ emissions of coal power plants at the generating unit level for the year 2012. Using the latitude and longitude of coal powered generating units from Oberschelp et al (2019), we aggregated the coal power plant emissions at the state level for India. We use Central Electricity Authority (CEA)’s data to determine total electricity generation in Indian states in 2012 (Central Electricity Authority 2012). To calculate the emission factor, we divide emissions from coal-fired electricity generation in each state by the total electricity generation in the same state to arrive at state level PM$_{2.5}$, SO$_2$, NO$_x$, and CO$_2$ emission factors (in g (kWh)$^{-1}$) for electricity generation. The estimates of state and regional level emission factors for India’s grid electricity generation are reported in supplementary information S2.4.

3.6. Energy costs and savings
To estimate the mass of fuel used, our analysis assumes that auxiliary engines produce ∼720 g of CO$_2$ per kWh for RO and ∼680 g of CO$_2$ per kWh for MGO (Entec 2002, Starcrest Consulting Group 2013). We assume an emission intensity of ∼3.1 kg CO$_2$ per kg (Entec 2002) of fuel burnt for marine fuel (Entec 2002). Thus, RO produces ∼4.3 kWh kg$^{-1}$ fuel and MGO produces ∼4.5 kWh kg$^{-1}$ fuel. In combination, these numbers allowed us to estimate the mass of bunker fuel needed to produce the required energy. We obtained the price per ton (19 December 2018) of both RO ($445 per metric ton) and MGO ($725 per metric ton) from Petrol Bunkering Group in Colombo Port, Sri Lanka (Petrol Bunkering & Trading 2018) and multiplied this by the mass of fuel consumed during a vessel call to calculate the fuel cost. The attractiveness of shore power depends on the local price of electricity. Therefore, we used the state-average price of electricity for the industrial and high-voltage consumers from their respective electricity regulatory commissions and converted from rupees to dollars per kWh using the market exchange rate on 30 November 2018 (Currency Converter 2018). These tariffs were used to calculate the fuel cost for supplying shore power to the vessels and are reported in supplementary information S2.5. For each vessel call, we subtracted the cost of electricity from the cost of RO or MGO to calculate the net savings and estimated the total savings from shore power that would accrue to the vessel over its remaining lifetime. Because 96% of the vessels in our dataset are less than 27 years old, we choose 27 years as the vessel lifetime and calculated the net present value of annual savings using a discount rate of 7%. Assuming that shoreside facilities to supply power exist, if the present value of these savings exceeds the cost of retrofitting the vessel, a vessel operator would reduce costs by retrofitting to receive shore power.

3.7. Comparison with total emissions in the area
We used the Emission Database for Global Atmospheric Research (EDGAR) 2015 emissions inventory (Joint Research Centre 2019) to estimate the proportion of the pollution in the major port cities that is caused by OGVs. We selected 0.1° × 0.1° cells to include the port cities we were studying. We ensured that the selected cells included the international and domestic airports, oil refinery, and the industrial areas of those cities. Specific information on the geographical extent of selected areas is in supplementary information S2.6. The most recent year for which the EDGAR emissions inventory is available is 2010. To project emissions to 2017 and beyond, we assumed that those emissions would grow in line with the economy and with the volume of trade in goods through Indian ports. We assumed that, between 2020 and 2030, emissions of all pollutants from international and domestic air transport, industrial and residential sectors grow at 6% per year (OECD 2018), in line with Organisation for Economic Co-operation and Development’s (OECD) projections for India’s gross domestic product growth in 2020–2030. From 2007 to 2017, the volume of seaborne trade through Indian ports grew at 3% (Government of India 2018b, IndiaStat 2020). We assume a 3% growth rate each year for Indian shipping and run a sensitivity analysis
for the 18% growth rate projected by GoI (Assocham 2017, Government of India 2017) during 2017–2025. We conducted the analysis for both RO and MGO at both growth rates and assumed that these growth rates remain constant until 2030. We assumed that the non-marine transportation sector grows by 9.7% per year (Government of India 2014) until 2032, in accordance with the projections of the erstwhile Indian Planning Commission, as noted in Kaack et al (2018). Finally, we assumed that the power generation sector grows by 5% per year from 2017 to 2030 based on projections for 2015–2030 from a study of Indian thermal power plants (Center for Study of Science Technology and Policy 2018) and Brookings India electricity demand estimates for 2030 (Sahil and Tongia 2019). In our results, we account for the effect of cleaning up of the coal power generation sector between 2017 and 2030 by scaling the coal power plant emission factors. We reduce the NO₂ emission index by a factor of 10 (i.e. to 10% of its current value), SO₂ emission index by a factor of 20, and the PM₂.₅ emission index by a factor of 250 when considering the emissions from coal power generation during 2017 and 2030. These factors were derived from the new power plant emissions standards promulgated by the GOI and summarized in Table 1 of Center for Study of Science Technology and Policy (2018).

3.8. Health effects of pollution reduction
We estimate the percentage contribution of shipping emissions to the total city emissions in 2017 relative to EDGAR emissions inventory (Joint Research Centre 2019). We multiply the percentage share of shipping in the city (in 2017) and the percentage change in emissions at each port after switching from RO and MGO to shore power to estimate the percentage of pollution reduced in each city. We use the estimated reduction in city pollution for PM₂.₅, SO₂, and NOₓ to approximate potential health benefits. Table 2 of Lee et al (2015) provides estimates of absolute change in mortality across each of the Global Burden of Disease regions for a 10% change in local PM₂.₅ precursor emissions. From this, we estimated the change in mortality in South Asia, per unit change in emissions of PM₂.₅ precursor pollutants. As described in S2.7 and S3.6.1 of the supplementary information, we obtain a regional estimate of the change in premature mortality given a percentage increase in emissions of different particulate matter precursor pollutants (black carbon, SO₂ and NOₓ). After accounting for population in cities located near Indian major ports, we were able to make a very rough estimate of the annually avoided premature mortality in major port cities (see supplementary information S3.6.1).

3.9. Cost of grid extension, shore infrastructure, and vessel retrofitting
We estimate the cost of extending the distribution line from the nearest substation to the port to provide grid electricity supply at berth. We obtained the sub-station data from Power System Operation Corporation Limited (POSOICO 2020). The distribution network is assumed to be connected to a three-phase distribution transformer and a 33 kV line is sufficient to meet the hourly peak loads of auxiliary engines at each major port (details in supplementary information S2.8). The cost per mile (∼$25 000 per mile) of extending a 33 kV line was taken from GoI’s electricity authority guidance document (Central Electricity Authority 2018b) and its maintenance cost was assumed to be 3% of the capital cost (Central Electricity Regulatory Commission 2013, 2017).

The total cost of grid extension is the sum of line extension and line maintenance costs for all ports. Shore power projects usually have a life of 20 years (California Air Resources Board 2020a) and we use this as the useful life of the shore power system. The cost of installing a shore power system at the port is assumed to be ∼$4.5 M based on estimates from shore power equipment manufacturers. To determine the total number of shore power systems required by the ports, we find the number of vessels simultaneously docked at each port during each hour of the year. We assume that the maximum of this number represents the number of charging points needed at each port. The total cost of deploying shore power systems is determined by summing the cost of installing shore power systems across all ports. The cost to the vessel operator of retrofitting a ship with shore power infrastructure (including cabling, switchboards, transformer, frequency converters and mechanical modifications) is between $300 K and $2 M (International Council on Clean Transportation 2015). The total cost of retrofitting is determined by summing the cost of vessel retrofit for all the berthed vessels.

4. Results and discussion
Our analysis is based on a dataset, which we believe is comprehensive, of the 21 937 port calls that 5732 unique vessels made to the 12 major Indian ports in 2017–18 (see supplementary table 9). The average berth duration across all ports was ∼50 h per vessel per call. Table 1 shows that the calls were dominated by tanker ships (chemical tankers, oil products tankers, liquefied natural gas (LNG) and liquefied petroleum gas tankers), bulk carriers and container ships. On average, bulk carriers had the longest stays averaging three days per berth call. Auto-carriers had the shortest stays, averaging just over one day per berth call. Averaged across all types of vessels at each port, the shortest average vessel call duration was for JNPT in Mumbai (28 h). The longest average vessel call duration was at the ports of Kolkata (77 h) and Haldia (53 h).
2019 explains the change in emissions for differences in supplementary table 26. For the case of Bharat Stage VI, which will reduce the sulfur content of road diesel by a factor of 50, come into force. As such, Bharat Stage VI, which will reduce the sulfur content of road diesel by a factor of 50, come into force. This growth is due to the reduction of the share of NOx emissions at some ports. The emissions from berthed ships burning MGO as a percentage of total city emissions in 2017 and 2030 are shown in Figure 2 (see supplementary table 26). For the case where berthed ships burn RO, their percentage contribution to total city emissions in 2017 and 2030 is included in supplementary table 25. If shipping activity were to grow in line with the sensitivity analysis scenario wherein the volume of trade grows at 18% annually (Assocham 2017, Government of India 2017), we anticipate the relative proportion of emissions from ships to increase (see supplementary tables 27 and 28). This growth is due to the reduction of the emissions intensity of other sectors as standards such as Bharat Stage VI, which will reduce the sulfur content of road diesel by a factor of 50, come into force. India has also started to require that SO2, PM2.5, and NOx emissions from coal fired power plants—which have so far been unabated—be drastically reduced by implementing post-combustion treatment of flue gases (Center for Study of Science Technology and Policy 2018), (Central Electricity Authority 2017). In this case, NOx emissions from berthed ships will constitute a major portion of the total city emissions.

### 4.1. Environmental consequences

#### 4.1.1. Relative contribution of major port emissions to total city emissions

Ships berthed at major ports are a significant source of local SO2 and NOx emissions in Indian port cities. If shipping activity were to grow at 3% per year (2007–2017 Indian shipping growth rate) (Government of India 2018b, IndiaStat 2020) and ships continued to burn RO or MGO, then the relative share for emissions from berthed ships for both fuel types decrease in 2030, except for increase in shipping's share of NOx emissions at some ports. The emissions from berthed ships burning MGO as a percentage of total city emissions in 2017 and 2030 are shown in Figure 2 (see supplementary table 26). For the case where berthed ships burn RO, their percentage contribution to total city emissions in 2017 and 2030 is included in supplementary table 25. If shipping activity were to grow in line with the sensitivity analysis scenario wherein the volume of trade grows at 18% annually (Assocham 2017, Government of India 2017), we anticipate the relative proportion of emissions from ships to increase (see supplementary tables 27 and 28). This growth is due to the reduction of the emissions intensity of other sectors as standards such as Bharat Stage VI, which will reduce the sulfur content of road diesel by a factor of 50, come into force. India has also started to require that SO2, PM2.5, and NOx emissions from coal fired power plants—which have so far been unabated—be drastically reduced by implementing post-combustion treatment of flue gases (Center for Study of Science Technology and Policy 2018), (Central Electricity Authority 2017). In this case, NOx emissions from berthed ships will constitute a major portion of the total city emissions.

#### 4.1.2. Annual emissions from ships berthed at major ports

The annual PM2.5, SO2, NOx and CO2 from ships burning RO at major Indian ports was 850, 7700, 9500 and 470 000 tonnes, respectively (see supplementary table 29). If ships were to burn MGO, then the annual PM2.5, SO2, NOx and CO2 at Indian major ports are estimated to be 190, 1400, 900 and 450 000 tonnes respectively (see supplementary table 29). Our analysis has produced a unique annual hourly inventory of PM2.5, SO2, NOx and CO2 emissions from berthed vessels for India’s 12 major ports (details in supplementary information S3.3).

#### 4.1.3. Change in emissions if vessels switch to shore power

Because of the low sulfur content of MGO, and assuming that the high sulfur intensity of India’s power system remains unchanged when vessels are required to burn MGO, if vessels switched from burning MGO to shore power, net emissions of PM2.5 would decline by 46% (86 tonne reduction); NOx emissions would fall by 84% (7500 tonne reduction), but SO2 and CO2 emissions would increase by 240% (3300 tonne increase) and by 17% (75 000 tonne increase), respectively (see supplementary tables 31 and 32). The case for the switch from RO to shore power is discussed in supplementary information S3.4. The annual PM2.5, SO2, NOx, and CO2 emissions from grid electricity in 2017 was 100, 4700, 1500, and 520 000 tonnes respectively (supplementary table 30).

Figure 3 explains the change in emissions for different pollutant categories when ships switch from burning MGO to shore power for the 12 ports we studied. For MGO, switching to shore power increases SO2 emissions across 11 out of 12 ports except for Cochin. This is due to the lower amount of sulfur emitted by the combustion of fuel in comparison to burning coal for electricity generation. The source of electricity generation in Cochin is hydro-power and thus SO2 emissions from the grid do not increase from the switch (Kerala State Electricity Board Limited 2019). We also estimate the change

### Table 1. Summary statistics of ships calling at major ports in India 2017–2018. A total of 5732 unique ships visited major ports during the year.

| Vessel class | Vessel calls | Unique vessels | Total hours (1000s) | Average call duration (hours) | Average auxiliary capacity (kW) | Total energy use (GWh) | Mean age (yrs.) |
|--------------|--------------|----------------|---------------------|-------------------------------|--------------------------------|-----------------------|-----------------|
| Auto Carrier | 343          | 181            | 9                   | 26                            | 730                            | 6.6                   | 13              |
| Bulk         | 5833         | 2560           | 430                 | 74                            | 380                            | 170                   | 9               |
| Container    | 4933         | 577            | 170                 | 35                            | 640                            | 95                    | 13              |
| Crude oil    | 1210         | 444            | 56                  | 46                            | 1100                           | 60                    | 13              |
| Tanker       | 2292         | 575            | 150                 | 64                            | 630                            | 100                   | 14              |
| General Cargo| 473          | 40             | 25                  | 54                            | 2800                           | 54                    | 20              |
| Passenger    | 23           | 12             | 1.5                 | 63                            | 95                             | 0.16                  | 10              |
| RoRo         | 6830         | 1343           | 270                 | 39                            | 610                            | 160                   | 12              |
| All major ports | 21 937     | 5732           | 1100                | 50                            | 630                            | 650                   | 13              |
in emissions when ships switch from burning RO to shore power across major ports (see supplementary figure 9, supplementary table 31 and supplementary table 32). For RO, switching to shore power increases SO$_2$ emissions at Chennai, VOC, Kamarajar and Paradip ports. Chennai, VOC and Kamarajar are located in the state of Tamil Nadu, where lignite is burned for power generation (NLC India Limited 2019). Paradip port is located in the state of Odisha (eastern India), where low grade coal from Mahanadi Coalfields is used for power generation (see supplementary figure 10) (Coal India Limited 2020, NTPC 2020). Because of the low quality of coal use, the emissions factors for generating units in Tamil Nadu and Odisha are an order of magnitude higher than other states (see supplementary table 17).

Figure 2. Annual emissions contributions for PM$_{2.5}$, SO$_2$, NO$_x$, and CO$_2$ to total city emissions in (a) 2017 and (b) 2030 from berthed ships burning MGO at major ports. The shipping growth rate in ((a), (b)) is assumed to be 3% per year (2007–2017 Indian shipping annual growth rate) (Government of India 2018b, IndiaStat 2020).
4.2. Annual fuel cost savings due to switching from fuel oil to shore power
The median savings per vessel call for switching from RO and MGO to shore power is $210 and $1500, respectively (see supplementary table 34). The median annual fuel cost savings per vessel for switching from RO to shore power is $610 and the median annual fuel cost savings per vessel for switching from MGO to shore power is $3700 (see supplementary figure 11(a)). The savings are greatest for bulk carriers, tanker and general cargo ships.

Over the expected life of all vessels, using a discount rate of 7%, switching from RO and MGO to shore power yields a net private benefit of $73 M and $370 M, respectively (see supplementary table 33). While the median lifetime savings per vessel for switching from RO to shore power is $5300, the median lifetime savings per vessel for switching from MGO to shore power is $33 000 (see supplementary figure 11(b)). The typical cost of retrofitting a vessel is $300 K–$2 M (International Council on Clean Transportation 2015). For RO, only 0.2% of the vessels (9 vessels) had annual savings above $300 K and for MGO, 2.4% of the vessels (138 vessels) had savings above $300 K. Thus, very few ship operators would reduce their fuel costs enough to pay for the cost of retrofitting their ships for shore power.

4.3. Health consequences
It is difficult to quantify the effect of a shift to shore power on premature mortality without running integrated air quality assessment models. However, a zeroth-order analysis, performed by treating each city as a homogeneous well mixed region suggests that switching from RO to shore power in the absence of emissions regulation for power generation and transportation sector might avoid of the order of 40 premature deaths each year (see supplementary table 35). Switching from MGO to shore power might avoid roughly five premature deaths each year (see supplementary table 36).

If shipping grows at 3% per year, (Government of India 2018b, IndiaStat 2020) as it has in the decade from 2007 to 2017, while power generation and road transportation become cleaner, switching from RO and MGO to shore power in 2030 would avoid roughly ten premature deaths each year (supplementary tables 37 and 38). Figures 4(a)–(d), respectively, show the health benefits of switching from RO and MGO to shore power in 2017 and 2030, although these numbers are highly uncertain.

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**Figure 3.** Change in total emissions (in tonnes) for (a) PM$_{2.5}$, (b) SO$_2$, (c) NO$_x$, and (d) CO$_2$ at major ports, if ships were to use shore power instead of burning MGO for meeting their electricity requirement. Baseline emission factors are based on the grids of the state in which the port is located. However, the high and low estimates (indicated by the yellow whiskers) are based on East, West, North, and South regional grids.
Figure 4. Estimates of premature deaths avoided across major ports by switching from RO (a), (c) and MGO (b), (d) to shore power in 2017 and 2030 by treating each city as a homogeneous well mixed region. The growth in shipping is assumed to be 3% each year (Government of India 2018b, IndiaStat 2020) and the error bars represent 95% confidence interval (CI).

and should merely be treated as an indication that the effect of shore power on premature mortality is likely to be small. For RO, the analysis suggests that, in Tamil Nadu, any shift to shore power would increase premature mortality, since much of the state’s electricity is generated by burning lignite. Further, this suggests that the decision of the VOC port in Tamil Nadu to start deploying shore power (Maritime Executive 2017) at VOC-II and VOC-III berths (Chidambaranar Port 2018) may actually be detrimental to air quality and human health. Until the GoI enforces its proposed regulations for cleaning the power generation sector, switching from MGO to shore power would increase premature mortality in the states of Goa, Gujarat, Tamil Nadu, and West Bengal. On the other hand, if shipping grows at 18% per year (Assocham 2017, Government of India 2017) as India’s MoS projects, while power generation and road transportation become cleaner, switch from RO and MGO to shore power in 2030 would avoid roughly 100 and 40 premature deaths annually (see supplementary figure 12, supplementary tables 39 and 40).

In the absence of chemical transport models, it is possible to qualitatively assess the effect of a switch to shore power on the concentration of pollutants. A switch from fuel oil to shore power moves pollution emissions from high population density areas (near the port) to a lower density area (near power plants). For example, an analysis of the wind rose for the city of Cochin (refer to supplementary figure 14) shows that pollution from the port is likely to be blown toward densely populated areas of Cochin for 9 months of the 12 months of the year. The nearest coal-fired power plant (Mettur Thermal Power Station; capacity: 1440 MW) is situated ~260 km away and has a population density of ~730 people per km$^2$ in nearby region. As such, our initial hypothesis would be that any reduction in pollution at the port would improve the air quality over Cochin and be beneficial for the health of its residents. The effect is similar across other major ports including the ones where electricity generation is coal based (see supplementary information S3.6.2).

4.4. Cost effectiveness of shore power in India

The total cost, for all 12 ports, of constructing and maintaining overhead power lines from the nearest substation to the port is $1.5 M (i.e. an annual amortized cost over 20 years, discounted at 12% of ~$200 K). Our analysis showed that, to obtain the benefits described above, 249 berths would need to be equipped for shore power across the country. The total cost of installation of shore side infrastructure for all the ports is ~$1.1 B. This translates roughly to an annual amortized cost of ~$140 M–$150 M. Given that we estimate that a shift to shore power
from RO is likely to avoid of the order of 40 premature deaths each year, this suggests a cost effectiveness of ∼$4 million per premature death avoided. If ships use low-sulfur fuel (e.g., MGO), little public health benefit is likely to accrue. As discussed previously, for vessel operators, the benefits of shore power, as measured by lower fuel costs, are unlikely to exceed the costs of retrofit. We also conducted a sensitivity analysis to the local price of electricity for RO and MGO. This has been discussed in supplementary information S4.2.

4.5. Effect of renewable electricity generation
We estimate the cost of supplying electricity to berthed ships via installing grid connected solar photovoltaic (PV) systems in the ports. The net cost of installing solar PV systems to the port including system capital cost, maintenance cost, feed-in revenue to the port and electricity procurement cost across the major ports is ∼$0.4 B (see supplementary information S4.3). This translates to annual amortized cost of $52 M–$55 M to the ports, net of the avoided cost of purchasing electricity. Since it is reasonable to assume that the marginal source of electricity at all locations in India is currently always unabated coal, a switch to a solar PV system sized to supply the annual demand for electricity for berthed ships would produce zero net emissions and completely eliminate the emissions generated by burning oil (RO/MGO). For ships burning RO, a switch to solar PV would avoid roughly 50 premature deaths each year (see supplementary table 45) resulting in a cost effectiveness of ∼$1 M per premature death avoided. In the case of ships burning MGO, this will avoid roughly 20 premature deaths (see supplementary table 46) with a cost effectiveness of ∼$3 M per premature death avoided.

5. Conclusions
Our results indicate that for most vessels, the cost to install the technology and enable the vessel to connect to shore power exceeds the net private benefit to vessel operators. The switch to shore power is unlikely to produce a net public benefit now or in the near future until the grid has become cleaner. On the basis of net private benefit, operators would choose to retrofit only about 0.2% of the vessels in our dataset to receive shore power. Thus, on its own, installation of the shore power infrastructure would not likely incentivize significant uptake of shore power use for vessels. In many cases, a shift to shore power would move pollution away from densely populated cities to the less densely populated areas where power plants are typically situated. Since it is impossible to quantify the effect of this shift without using chemical transport models, our analysis tacitly assumes that the ports and power plants are part of a single well-mixed cell. With this assumption, and given the current Indian electricity generation mix, we observe relatively modest public health benefits from a switch to shore power. Based on these results and without more detailed analysis—which our hourly emissions inventory could facilitate—the government would be ill-advised to incentivize vessel retrofits or to construct the costly infrastructure needed to provide shore power. We identify several sources of uncertainty and supplementary information S4.1 discusses how we address them.

India's trade with China is growing at ∼19% (PTI 2018) per year. China has declared DECA across its coastline and is promoting shore power use (Mao 2019). Here we have only accounted for vessel calls at major Indian ports. For vessels calling at both Chinese and Indian ports, and which have been retrofitted to receive shore power in response to Chinese regulations, it would be cheaper to use shore power at Indian ports than burning low sulfur fuel.

Our analysis provides some evidence that emissions at Indian ports could be cut by making ports more efficient. For example, our raw data suggest that at the port of New Mangalore, the loading and unloading rate in 2017 was ∼10 containers per hour, compared to ∼50 containers per hour at POLA in 2013 (Port of Los Angeles 2013).

In summary, until the bulk power supply in India is cleaned up, or ports develop their own cleaner sources of power, our study finds that switching berthed vessels to shore power at major ports in India is unlikely to yield a public benefit large enough to justify an investment that private sector actors are unlikely to make themselves. For this reason, national policy by GoI should focus on cleaning up the power sector in India.

Data availability statement
All data that support the findings of this study are included within the article (and any supplementary files).

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