Economics of shore power for non-liner shipping: Socioeconomic appraisal under different access pricing

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Axel Merkel, Erik Nyberg, Karin Ek & Henrik Sjöstrand

Transport Economics, VTI, Swedish National Road and Transport Research Institute

Abstract

The provision of shore power to ships at berth is recognized as an effective measure to reduce the external costs of maritime transport. However, the deployment and uptake of shore power technology is subject to barriers, part of which have to do with insufficient economic incentives for providers and users. Regulatory proposals in the EU have targeted liner shipping segments to be covered by a shore power mandate. There is much less discussion and research focused on other segments of shipping, though these represent a significant share of at-berth emissions. This study uses maritime traffic data and a relatively simple modelling framework to analyse whether public investments in shore power deployment, coupled with added incentives to shipowners, could be socio-economically beneficial. The analysis is focused on maritime traffic in the Swedish port network, but the main findings can likely be generalized beyond this context. We find that investing in (or mandating) the provision of shore power in ports can be socio-economically beneficial also when aimed at segments typically classified as non-liner (or "tramp"). The results do not however indicate that network-wide deployment of shore power is justifiable, but rather that care must be taken to determine the cost-efficient size of the network as well as to design the network of shore power deployment in ports so as to reap benefits of network effects. We also find that the pricing of shore power access has a major impact on expected uptake and consequently on whether or not shore power investments yield benefits in proportion to costs. Crucially, we find that unregulated profit-maximizing pricing by ports leads to significant welfare losses by suppressing take-up among shipowners.

Keywords

Shore power; On-shore power supply, Infrastructure pricing; Cost-benefit analysis; CO_2 emission reduction

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1. Introduction

The provision of shore power (also called cold ironing, onshore power supply, shore-side power, shoreside electricity, alternative marine power, high-voltage shore connection) to ships is recognized as an effective measure to reduce CO_2-emissions as well as air pollution from maritime transport (Innes & Monios, 2018; Zis, 2019; Stolz et al., 2021), though the realization of this potential is subject to barriers, some of which are economic. Uptake of shore power on ships requires costly retrofitting, which only makes economic sense for a shipowner if a sufficient number of visited ports provide shore power, which in turn requires costly investment and is only profitable once a reliable number of ships are able to use (and pay for) the facilities. This has been described as a 'chicken-and-egg' dilemma (Zis, 2019; Wu & Wang, 2020; Wang et al., 2021).

Through its proposed Fuel EU Maritime regulation, the European Commission (2021) has set its sights on mandating that container and passenger vessels connect to shore power for stays in EU ports longer than two hours. While it is true that container, passenger, and other liner shipping segments account for the majority of CO_2 emissions at berth, a non-negligible share of berth emissions are produced by vessels outside typical liner segments. Using Sweden as an example, available data computed for 2018 (Stolz et al., 2021) show that the combined CO_2 emissions at berth for the oil tanker, gas carrier, bulk carrier, general cargo ship and chemical tanker segments account for roughly 25 percent of all ships' CO_2 emissions at berth.[2] Despite this, there are thus far no suggested national or European mandates for the uptake of shore power in non-liner segments of shipping.[3]

A central part of the problem in shore power investment and uptake is related to the dispersion of traffic patterns. For a vessel with a high number of scheduled calls at only a few ports, a retrofitting investment to connect to shore power is more likely to generate a reliable payoff than if its port call pattern is dispersed and unpredictable. Likewise, ports where calls are concentrated to a small number of ships are more likely to see a positive business case in providing shore power facilities than ports with a large number of non-frequent users (for whom uptake is not likely to be profitable). For non-liner ('tramp') shipping, it can be hypothesized that more intense policy measures are needed to foster investment and uptake in shore power since the business case is weaker on its own. However, it is not certain that shore power investments in non-liner shipping terminals and ships is justified on a socio-economic basis. Whether this is the case depends on the calling patterns of vessels in the port system,

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[2] The same data (Stolz et al., 2021) shows that the electrification of all energy demand from ships at berth in Sweden would require electricity equivalent to roughly 0.15 percent of total domestic electricity production.

[3] Liner shipping refers to vessels operating a fixed set of routes on a schedule, e.g., container or ro-pax vessels. Non-liner (or 'tramp') shipping refers to vessels not operating on such regular services. For the purposes of this paper, we analyze shore power for three shipping segments: tankers, bulk carriers and general cargo ships. While there are examples of vessels in these segments operating on fixed schedules, the majority of services can be described as non-liner and as a simplifying measure we opt for this description of the segments included in the analysis. We also include an analysis of container ships to provide a reference to our main results.

the costs of investment, the relative prices of electricity and marine fuel, the laytime and potential for emissions reduction from calling vessels and, perhaps crucially, the pricing policies of ports. One way around the ‘chicken-and-egg’-dilemma is for the public sector to move first by undertaking (or mandating) investments in shore power, in order to provide access to ships whose owners make reciprocal investments in shore power uptake. However, such actions require an understanding of how much shore power deployment is efficient and how shore power access is to be priced once available. This issue is investigated in the present paper.

In this paper, we develop a relatively simple model to calculate the uptake, emissions reduction potential and socio-economic impacts of shore power for bulk carriers, tankers and general cargo ships using Swedish maritime traffic data. We also show how the socio-economic viability differs between liner and non-liner shipping by including an analysis of shore power for container ships as reference. Considering a currently active tax reduction on berth electricity, a variety of cost inputs, and network effects of expanding shore power, we find that investments in shore power facilities can be socio-economically beneficial for all studied segments, though the optimal extent of deployment and the level of socio-economic profitability depends on whether ports’ pricing of shore power access is welfare-optimal or profit-maximizing. For all studied segments, we find significant welfare losses associated with unregulated port pricing and conclude that welfare-optimal pricing (or equivalent forms of subsidies to vessels compensating the reduced social cost of emissions) is necessary in order to realize the maximum societal benefits from shore power.

2. Previous research

In the literature regarding shore power, there is a lot written about the economics and potential for emission reduction, but less on how access to shore power should be priced and what impact this has on uptake. From the economic side, shore power will demand costs in the form of ships needing to be retrofitted or built with more expensive technology, in addition to large investments for ports in more costly terminals. The benefits, e.g., decreased emissions and reduced noise levels, are, however, often shown to outweigh the cost for society at large (e.g., Zis, 2016; Zis et al., 2019). Regardless, even if the implementation would be net-positive from a socioeconomic viewpoint, there is still the question of profitability for both the shipowners and ports which needs to be addressed.

A tool was developed for economic evaluation of shore power using cost-benefit analysis (CBA) by the World Ports Climate Initiative (2016), which allowed for an evaluation of either the business case for the port and shipowners together, involving investments in terminals and ships as well as operational costs, or from a socioeconomic viewpoint, which also included monetization of emissions, such as CO_2. The cost of electricity was included as an electricity price and tax, as well as contract and electricity transport costs. Ballinin and Bozzo (2015) evaluated the negative health aspects of air pollution in ports and the economic benefits of shore power for a cruise ship pier in Copenhagen using a model called the External Valuation of Air Pollution Model. Under certain assumptions (e.g., the share of retrofitted cruise ships), their CBA showed that investment cost of the port was recuperated through reduced health costs in 12–13 years, excluding the positive externality of reduced CO_2-emissions. Similarly, Innes and Monios (2018) investigated the feasibility of installing shore power in a medium-sized port, Aberdeen, using CBA and analysing different payback scenarios. With a reduction in CO_2, NO_X, and PM, the authors estimated that the benefits would yield a positive return on investment after 7–14 years. Spengler and Tovar (2021) also describe the benefits of shore power towards the society in general and particularly port cities, within the Spanish context. They argue that shore power is expensive purely as a measure for CO_2-abatement but that this changes when including other externalities (NO_X, SO_X, and PM).

Additionally, in a report by the British Ports Association (2020), barriers for the implementation of shore power technology in Great Britain were evaluated. In a survey of the association's members, the main barriers to adapting shore power were described as the capital cost of investment, cost of electricity, and lack of demand from the shipping companies. The latter comes up frequently in the literature as the chicken-and-egg-dilemma (see e.g., Zis, 2016; the British Ports Association, 2020; Wang et al., 2021), where shipowners won't invest in retrofitting ships unless more ports offer shore power, while ports delay investing in the provision of electrical power to ships if they cannot be assured that they can recuperate their costs. The British Ports Association argues that a scenario where ports were to transfer all their expenses and costs associated with shore power onto the shipowners would lead to hampered demand.

Multiple articles argue for more governmental intervention to get around the chicken-and-egg problem. This is addressed in, for example, Wang et al (2021), where governmental subsidy structures regarding shore power in ports are modelled within a framework to find the optimal level between subsidies that target shore power construction (direct subsidies to ports for terminals) and shore power operations (indirect to ship-owners through reduced energy prices), with regards to at-berth CO_2-emission reduction per monetary unit (g/USD). The model, based on some assumptions of parameters (e.g., grid electricity price, port service charge, and price sensitivity of ship-owners), finds the optimal ratio of the two subsidy categories as well as the optimal sum of total subsidy. Likewise, Wu and Wang (2020) created a model that developed a governmental subsidy program that set out to reduce the at-berth emissions of a container shipping network. The framework is a two-stage optimization problem, in which a government first develops a shore power subsidization plan, and ports and shipowners thereafter make decisions based on the plan and subsequent network effects. Similarly, Dai et al. (2019) presented a framework for assessing the feasibility of shore power investments that incorporates profits from an emission trading scheme to incentivize ports to invest in the technology. When modelling the costs and revenues for 10 years, the result revealed that the income from emission trading on its own was not enough – the ports needed to make a profit on the electricity delivered to recuperate their investment. This was shown to be especially important in the case of the port of Shanghai, where an electricity sale price cap exists.

In addition to articles regarding the larger economics of shore power implementation, there are ones that evaluate shipowners’ costs associated with shore power and the implementation of the technology. For example, Yiğit et al. (2016) evaluate the unit energy cost of electricity for bulk carrier ships utilizing different conventional fuels as well as the theoretical cost of shore power at international ports in 31 countries. The authors find that using shore power technology would be beneficial in many ports, reducing unit energy costs of up to 75%. Sisson and McBride (2011) compared best-case and worst-case scenarios for shipowners in the US from an energy cost-perspective, for both conventional operations and shore power. Similarly, Martínez-Lopéz et al. (2021) introduced a calculation method to estimate environmental charges in ports to incentivize the introduction of shore power, and thereby internalize the external cost of air pollution. The focal point of the paper is with the shipowners, where the environmental charge is to be laid upon ships not utilizing shore power, with a level based on the difference between emission from the used technology (conventional fuels) and the most sustainable alternative (shore power). Three case studies from Spain were included, where the analysis on the charges’ effect on economic performance of shipowners are performed through calculating internal rates of return. Electricity prices are unitary and taken from existing shore power facilities in Spain, and neither port charge rebates nor public support for retrofitting ships were included in the analysis. Lastly, a sensitivity analysis was performed using Monte Carlo simulations, where factors such as electricity prices, fuel prices, environmental charge, ship duties, and retrofitting investments are varied.

Lastly, there are a few articles that evaluate the effect of pricing scheme for the implementation of shore power. Qiu et al. (2022) present a multi-level pricing framework of shore power services for all-electric ships. The framework considers voyage scheduling of ships, the power system dispatch, and the profit-maximization (under conditional value at risk) of ports, based on a time-of-use pricing model where price structure and levels are optimized jointly. The model includes CO_2-emissions with a carbon pricing modelled called distribution locational marginal pricing. In simulation with three ports, the pricing structure is compared to a case without shore power, real-time pricing of shore power, and flat-time pricing of shore power. The authors argue that their model satisfies all parties: the ports maximize their profit (under conditional value at risk), shipowners lower their risk by avoiding real-time pricing with charging planning, and congestion and emissions are minimized. Zis et al. (2019) also provide a methodology to evaluate investments in shore power and their cost-effectiveness, from the perspective of stakeholders such as ports and shipowners. Case studies of different global routes help evaluate the net present values of retrofitting different ship types, based on penetration rates, fuel prices, and interest rates. For the evaluation from the ports’ perspective, three different shore power pricing behaviours are included: ‘neutral’ (sell at cost of purchase), ‘super green' (give away for free), and 'greedy' (sell at profit, 10 % lower cost than fuel at port). The costs for abated emissions (CO_2 and NO_X) are shown to be larger for the super green port compared to the neutral one. Abatement costs are found to be lower than valuations of negative externalities, making it an economically feasible technology to reduce emissions.

3. Method

3.1 Shipowners' and ports' profits from shore power investment

The annual profit to a shipowner (s) from investing in technology to connect to shore power can be expressed as

$$\pi_s = \sum_j A_j E_j \left[P_f Q_f - P_e Q_e - C_p\right] - C_r$$

Where A_j is the annual number of port calls made by the individual ship at port j, P_f is the price of marine fuel, Q_f is the quantity of marine fuel consumed by auxiliary engines during a port stay, P_e is the electricity price ships face (including the spot market price, grid fee and tax net of any applicable rebate), Q_e is the electricity demand required to satisfy output by auxiliary engines during a port stay (taking into account energy losses from conversion), C_p is an access charge per stay levied by ports and C_r is the annualized investment cost in ship retrofitting.[4] E_j is a binary variable reflecting whether a port has invested in the provision of electricity at berth or not. We assume the port charges vessels per call, rather than a markup on consumed electricity since charging a markup on shore power is prohibited by Swedish legislation. However, since we assume the port can differentiate charges, a vessel-specific fixed cost per call can in practice be used to replicate a variable charge per unit of electricity consumed.

The annual profit to a port (p) from investing in the provision of shore power can be expressed as

$$\pi_P = \sum_i A_i D_i \left[C_{p,i} - C_a\right] - n_b C_b$$

Where A_i is the annual number of port calls made by vessel i at the port, $C_{p,i}$ is the access charge levied on the ship, C_a is the port's marginal cost of connecting the vessel to shore power, D_i is a binary variable reflecting whether the ship is shore power ready, n_b is the number of berths with shore power access and C_b is the annualized investment cost associated with shore power access provision per berth.

The profit-maximizing access price C_p to charge any particular ship is the price that extracts all profit from the shipowner, while just maintaining a positive incentive for the shipowner to retrofit. Using the

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[4] The annualized investment cost is calculated as $C_r = C_{inv}\frac{r}{1-(1+r)^{-t}}$, where C_{inv} is the total investment cost, r is the rate of discount and t is the asset lifespan.

shipowner's profit function, we can find the access charge for a given ship which yields zero shipowner profit:

$$C_p^* = \max\left(P_f Q_f - Q_e P_e - \frac{C_r}{\sum_j A_j D_j}; C_a\right)$$

Which is either the difference between the per-call cost saving of connecting to shore power ($P_f Q_f - Q_e P_e$) and the retrofit cost divided by the number of visits at shore power-equipped berths or, in case the level of charge needed for zero shipowner profit falls short of the marginal cost of providing shore power access (which would result in negative revenues for the port), the marginal cost is charged. The above formulation implies that if ports charge the profit maximizing price of each vessel, all of the economic surpluses will accrue to the port. In the assumed model, charges vary between ships but not between ports for the same ship.

If the port is not charging for profit but for welfare maximization, the reduced external costs of air pollution and CO_2 emissions per port call following a shore power investment need to be taken into account. This reduced external cost can be expressed, per ship, as

$$\Delta C_e = \sum_j A_j E_j \left[E_{CO2} Q_f P_{CO2} + E_{AP} Q_f P_{AP}\right]$$

Which is the product of vessel calls at shore power-equipped berths and the sum of CO_2 and air pollution costs. The emission factor (tons emitted per ton fuel consumed) for CO_2 is denoted E_{CO2} and the valuation per ton CO_2 is denoted P_{CO2}, while E_{AP} denotes a vector of emission factors for relevant air pollutants and P_{AP} is a vector of their respective valuations. We assume here that grid electricity is produced without external cost, which is a reasonable assumption for Sweden (Börjesson et al., 2021; Stolz et al., 2021).

The first-best optimal user charge is the social marginal cost. Since shipping emissions at berth are presently not subject to any internalizing taxes in Sweden, the benefit caused by changes in emission costs is entirely external to the shipowner. The port charge $C_{p,w}^*$ which maximizes societal net benefits is therefore the marginal cost to the port of providing shore power access and the external marginal cost, which is negative:

$$C_{p,w}^* = C_a - \left[E_{CO2} Q_f P_{CO2} + E_{AP} Q_f P_{AP}\right]$$

This means that the optimal port charge is in fact a subsidy for the (usual) case where the private marginal cost of shore power connection is smaller than the associated avoided external cost of emissions.

3.2 Modelling approach

In order to study the effect of port pricing objective on the achievable uptake and societal net benefits associated with investments in expanded access to shore power, we incorporate the above functions into an investment appraisal model. We treat investment in shore power facilities in ports as exogenous and evaluate, for a range of investment scenarios, the modelled uptake of retrofitting investments as a response to shore power capacity and the associated benefits to society under different assumptions regarding port pricing.

Considering $E = \{E_1, \dots E_j, \dots E_m\}$ as a vector of binary decision variables describing the shore power status of all m ports in the network, the net benefits to society of investing in shore power can be described as

$$NB|E = \sum_i \sum_j A_{i,j} E_j D_i \left[P_f Q_f - P_e Q_e - C_a\right] + \sum_i \sum_j A_{i,j} E_j D_i \left[E_{CO2} Q_f P_{CO2} + E_{AP} Q_f P_{AP}\right] - \sum_i D_i C_{r,i} - \sum_j E_j n_b C_b + \sum_i \sum_j A_{i,j} E_j D_i \left[Q_{e,i} t\right]$$

Which in simplified terms represents the net of i) cost savings from switching from marine fuel to grid electricity, ii) external cost reductions from lessened CO_2 emissions and air pollution, iii) investment costs for shipowners and in ports as well as iv) increased governmental tax revenue (t represents the per-kWh tax rate net of applicable rebates, which is also included in P_e) associated with switching from an untaxed to a taxed energy source. The choice of a shipowner to invest in retrofitting to be able to connect to shore power (D_i) as a response to shore power availability in ports (E), is modelled as

$$D_i|E = \begin{cases} 1 \text{ } if \left(\pi_{s,i}|E\right) \geq 0 \\ 0 \text{ } if \left(\pi_{s,i}|E\right) < 0 \end{cases}$$

The above formulation of net benefits and shipowners' investment decisions captures network effects inherent in shore power provision and uptake. Since ships typically call at several different ports in a network, each added point of shore power provision will increase the profitability of a retrofitting investment for a shipowner. In terms of investing in shore power provision in ports, these investments are not independent since the provision of shore power in one port may increase demand by fostering additional uptake, stimulating profitable investment in other ports. In short, the level of demand increases with the level of provision and the profitability of provision increases with demand. It is therefore plausible that a bundle of shore power investments is more profitable than the sum of isolated investments in the same ports.

The modelling approach is as follows. First, we calculate the net benefits to society of equipping each individual port with shore power. Then, we construct an optimal order of investments by calculating successively (for j in 1:m where m is the total number of ports in the system) which investment in provision would yield the highest marginal net benefit. This yields a total of m different investment scenarios, where scenario 1 represents investing in the (single) port where most net benefits would result and each successive scenario represents the addition of the most profitable (in terms of social net benefits) addition on the margin.[5] Then, we calculate for each investment scenario the uptake of shore power by shipowners, the extent of emissions reduction and the marginal abatement cost per ton of CO_2 under two different pricing assumptions. Under the assumption that ports price shore power access at the profit maximizing rate we use the expression for C_p^* derived above. Under the assumption that ports price access at the welfare maximizing rate we use $C_{p,w}^*$ as a pricing rule.

4. Data

As a main source of input data, we use a complete record of commercial vessel calls at Swedish ports during 2016 – 2019. This dataset contains details for each call, including date of arrival, port of origin/destination, ship type and IMO number, which enables matching with other datasets. We complement some missing features of this data with a dataset containing vessel-specific technical details provided by IHS Markit. The vessel call data excludes service vessels, ships used for local public transport and ships with gross tonnage smaller than 300.

Regarding investment costs for ships, we use cost estimations from the Global Maritime Energy Efficiency Partnerships Project (GloMEEP, 2020), which is an IMO initiative aimed at supporting the uptake of energy efficiency enhancing measures in shipping. Verifying estimated investment costs with shipowners is hindered by the fact that the uptake of shore power is very low in the studied segments. However, in order to assess the reliability of retrofitting cost assumptions, we have consulted Swedish shipowners who have or are in the process of retrofitting tanker vessels. These assessments have largely corroborated the reliability of the GloMEEP estimates.[6]

Investment cost estimates for ports are based on data from the Swedish ‘Climate Leap Initiative’ (Swedish Environmental Protection Agency, 2022), which has provided co-funding to several shore power projects. Figures from projects approved for governmental co-funding show that the average cost per shore power-equipped berth is around SEK 7 million (approximately EUR 0.67 million), though this is heavily dependent on how much work needs to be done in specific cases. For instance, if land-side frequency conversion is needed, investment costs can more than double. For both landside and ship investments we assume an economic lifespan of 15 years (15-20 years is typical in ports’ own appraisals of shore power investment) and a discount rate of 4 percent. Regarding ports’ marginal cost of providing shore power to vessels, den Boer and Hoen (2016) calculate the annual operating and maintenance costs of shore power as 5 percent of the investment cost. Assuming the above-described

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[5] For simplicity and due to lack of more granular port call data at the berth-level, we consider an investment in a port to amount to *all* berths serving vessels in a segment to be equipped with shore power. When we consider shore power to be deployed in a port, we calculate the number of required berths based on the number of calls in a vessel segment as $\sum_i A_i / (\frac{365}{l})$, where *l* is the average laytime in days, and round up.

[6] GloMEEP presents one high and one low set of retrofit costs per vessel type and size. In order not to understate the actual costs for shipowners, we use the higher set of estimates in the main analysis of this paper. In the sensitivity analysis (described later in the paper), we consider even higher costs of investment.

investment cost per berth of around EUR 0.67 million and a rate of 300 annual port calls per year, this works out at around 100 euros per vessel call, which is assumed in the main analysis.

Perhaps the most important input values in the appraisal model are the assumed prices of electricity and marine fuel since their relative size has a major influence on the incentive for shore power uptake. For electricity prices, we use the 2021 average spot price for medium and large non-household energy consumers (Statistics Sweden, 2022), which was SEK 0.56 (EUR 0.054) per kWh. In addition to the spot price, we assume a grid fee of SEK 0.2 (EUR 0.019) per kWh, which was the average during 2021.[7] The Swedish electricity tax in 2021 was SEK 0.356 per kWh, though shore power is subject to a tax reduction (which is paid retroactively to shipowners) of SEK 0.35 per kWh, meaning that the total applicable tax per kWh is only SEK 0.006 or EUR 0.0006. The price per kWh, including grid fees and taxes, is therefore equivalent to approximately EUR 0.074. We further assume an energy conversion loss of 8 percent (in line with Zis et al., 2014). For marine fuel prices, we assume a price per metric ton of low sulphur (ECA-compliant) marine gas oil of EUR 533, which was the approximate average Rotterdam price during 2021. For a specific auxiliary engine fuel consumption of 210 g/kWh, this works out at a cost of approximately EUR 0.112 per kWh of marine fuel powered energy consumption at berth.

With emission factors for CO_2 and air pollutants, we use values from the IMO (2020) fourth GHG study. Valuations of emission externalities are taken from the European Commission’s Handbook on the external costs of transport (van Essen et al., 2019). We include the emission of NO_X, SO_X and particulate matter (PM) as air pollution costs. Due to a lack of reliable data, we exclude reduced costs of noise from the appraisal.

Laytimes per vessel segment are calculated from historical AIS (ship positional) data for the same base year as is used for port calls per vessel.[8] To do this, we subset an entire dataset comprising all ship movements in the Baltic Sea area to match the vessels in our data. Then, we intersect ship movements with a set of shapes representing port areas in Sweden and calculate the average times at berth per call for each vessel segment. In order for calculated averages to represent representative berthing times, very short laytimes (< 5 hours) found in the data were ignored. We find that bulk vessels in our data spent on average 99 hours at berth per port call. The corresponding values for tankers and general cargo vessels are 32 hours and 28 hours. Container ships, by contrast, were found to spend on average 21 hours at berth per port call.

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[7] Sweden is divided into four electricity price zones. This division leads to the possibility of different prices in different parts of the country. For the purposes of the analysis in this paper, we use a national average price and ignore the possibility that prices vary by region.

[8] AIS data and geographical port area shapes were kindly provided by the Baltic Marine Environment Protection Commission (HELCOM).

Table 1 - Model parameter values used in main analysis

Model parameter	***Value / Range***	***Source***
Investment cost per quay (EUR)	673 000	SEPA (2022)
Electricity cost (spot) (EUR/kWh)	0.054	Statistics Sweden (2022)
Grid fee (EUR/kWh)	0.019	Statistics Sweden (2022)
Electricity tax (EUR/kWh)	0.0342	Statistics Sweden (2022)
Electricity tax reduction (EUR/kWh)	0.0337	Statistics Sweden (2022)
Retrofit costs (EUR)	[284 000 - 610 000]	GloMEEP (2020)
Auxiliary engine output at berth (kW/hour)	[110 - 2500]	IMO (2020)
Conversion loss	8%	Zis et al. (2014)
MGO price/ton (EUR)	533	Ship & Bunker (2022)
SFC aux (g/kWh)	[185 - 210]	IMO (2020)
Laytime (hours)	[21 - 99]	AIS
Marginal operating and maintenance cost (EUR)	100	
Emission factor CO2e (kg/kg consumed)	3.206	IMO (2020)
Emission factor Sox (kg/kg consumed)	0.00264	IMO (2020)
Emission factor Nox (kg/kg consumed)	0.05762	IMO (2020)
Emission factor PM (kg/kg consumed)	0.00097	IMO (2020)
Social cost CO_2 (EUR/ton)	100	van Essen et al. (2019)
Social cost SOx (EUR/ton)	6900	van Essen et al. (2019)
Social cost NOx (EUR)	7900	van Essen et al. (2019)
Social cost PM (EUR/ton)	18300	van Essen et al. (2019)

Table 1 summarizes parameter values and sources where applicable. Table 2 presents relevant summary statistics concerning the vessel and port call data used in modelling. All observations refer to complete port call data for the Swedish port network during the four-year period 2016-2019. As can be seen by comparing the number of calls per vessel and the number of ports visited per vessel across segments, bulk carriers tend to have a sparser port call pattern on average, visiting fewer ports and making fewer annual calls than tankers and general cargo ships. Container ships, by contrast, made more calls per vessel though at relatively few different ports which indicates a concentrated port call pattern.

Though the socioeconomic appraisal undertaken in this study considers annual costs and benefits over the lifespan of shore power assets, we assume a level of traffic equal to the average over a four-year timespan for the entire period. The use of multiple years of data is necessary in order to sort out sporadic vessel traffic from stable recurring flows. However, there is still uncertainty regarding whether vessel traffic patterns can be expected to continue during the lifespan of the studied investments. In our analysis, we assume no growth of vessel traffic in order not to amplify the risk of overestimating the net benefits of shore power.

Table 2 - Summary statistics, maritime traffic in four included segments

	Mean	***SD***	***Min***	***Max***
Bulk carriers				
Annualized number of calls per vessel in all ports	1.58	11.10	1	157
Number of ports visited per vessel, 2016 - 2019	1.58	1.45	1	14
Deadweight tonnage of vessels	43 906	22 128	838	95 746
Age of vessels	12.42	7.31	3	56
Tankers				
Annualized number of calls per vessel in all ports	4.59	15.63	1	221
Number of ports visited per vessel, 2016 - 2019	3.43	4.26	1	26
Deadweight tonnage of vessels	50 936	49 352	400	309 373
Age of vessels	14.29	6.12	3	54
General cargo ships				
Annualized number of calls per vessel in all ports	5.85	11.47	1	160
Number of ports visited per vessel, 2016 - 2019	6.71	6.63	1	36
Deadweight tonnage of vessels	7 348	7 866	772	95 731
Age of vessels	20.15	9.67	3	57
Container ships				
Annualized number of calls per vessel in all ports	7.48	13.64	1	82
Number of ports visited per vessel, 2016 - 2019	2.61	1.95	1	9
Deadweight tonnage of vessels	48 678	68 600	2 660	214 121
Age of vessels	15.23	6.13	3	40

The number of active ships and size of the network of visited ports differs between the studied segments. In the bulk carrier segment, the number of unique vessels during 2019 was 166 and the number of visited ports by these vessels was 35. In the tanker segment, the number of vessels was 1 329 and the size of the network of visited ports was 64. For general cargo ships, the number of unique vessels was significantly higher, 1 181, and the number of visited ports was 97. By contrast, the number of unique container ships in the data is 314 and the number of visited ports was 28.

5. Results

5.1 Optimal shore power deployment in ports per segment

Results of applying the appraisal model described in Section 3 are visualized for the bulk carrier segment in Figure 1. The left panel illustrates how increasing the number of ports in which to invest in shore power facilities increases the total net benefits up until the optimal level of deployment, which is to invest in the three ports where profitability is highest (indicated by the blue vertical line). Any further shore power deployment leads to smaller net benefits because the value of additional uptake in terms of energy cost savings and external cost reductions are more than outweighed by the additional costs of investment and marginal costs of use. The results show that under welfare-optimal pricing, which is in practice a subsidy scheme, annual net benefits to society would amount to EUR 0.2

million. Unsurprisingly, the net benefit achieved with the same investment package if assuming profit-maximizing access pricing is lower. However, it is interesting to note that even under profit-maximizing pricing, positive net benefits of shore power deployment can be achieved. In other words, shore power profitability is robust to alternative assumptions regarding access pricing.

The right panel illustrates the marginal abatement cost (per ton) of reducing CO_2 emissions by adding to the shore power investment package, assuming welfare-optimal access pricing.[9] It is notable that under none of the investment packages a MAC below the valuation of CO_2 is achieved. It is also notable that when we pass the optimal extent of shore power deployment (3), the MAC rises drastically, showing that a network-wide mandate of shore power deployment for bulk terminals would come at a very high cost per abated ton of carbon. Conversely, the right panel shows what level of CO_2 valuation (social cost of carbon) would need to be assumed in order for a certain level of deployment to be profitable on the basis of only reduced CO_2 emissions.

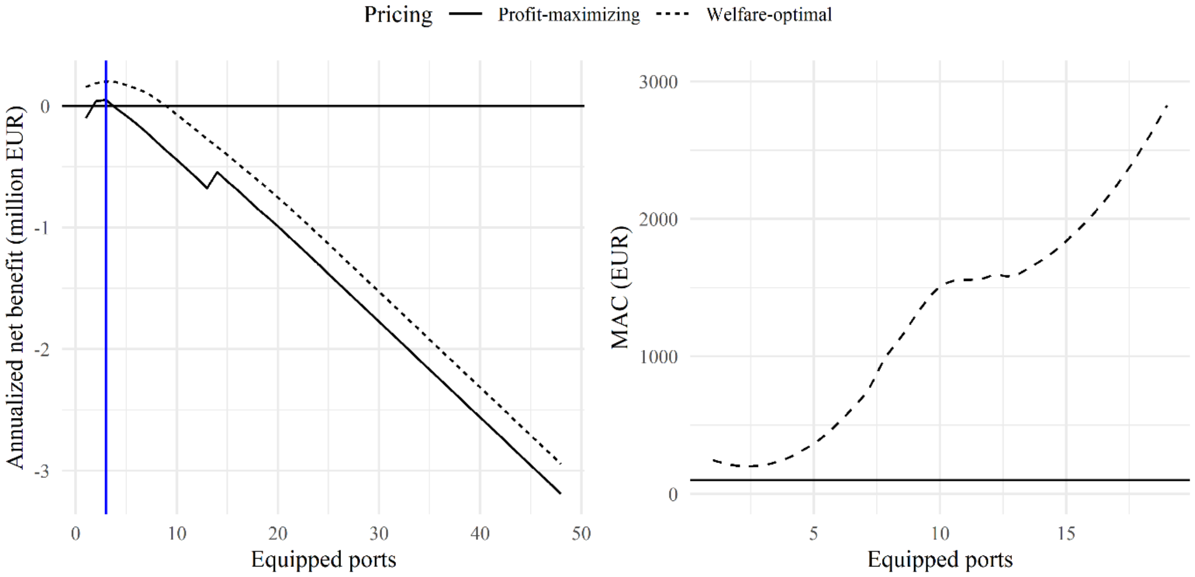

Figure 1 – Bulk carrier segment: Annualized net benefit (left panel) and marginal abatement cost (MAC) per ton of CO2 (right panel), for a range of investment scenarios. Blue vertical line in left panel illustrates the extent of shore power deployment which is most profitable in terms of net social benefits (under welfare-maximizing pricing). Black horizontal line in right panel is drawn at EUR 100, which is the per-ton CO2-valuation applied.

Figure 2 shows similar visual results for the tanker segment. From the left panel, it is clear that the net benefit curve assuming welfare-maximizing pricing flattens out at an investment size of around ten ports and the point at which no additional net benefit is achieved by further deployment is when a deployment size of 16 ports is reached. There is a significant gap between the net benefit realized through the different pricing policies of ports. In fact, the results show that unless shipowners are subsidized to compensate for reduced external costs of shore power uptake, no level of deployment

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[9] MAC-curves presented in this section are smoothed based on locally estimated moving averages.

can yield positive net value to society. This means that under the assumption of profit-maximizing pricing, no deployment of shore power is welfare-increasing.

The MAC-curve for tankers, illustrated in the right panel, shows that under the assumed CO_2 valuation, carbon emissions reductions alone are not enough to motivate shore power investments under any deployment scenario.

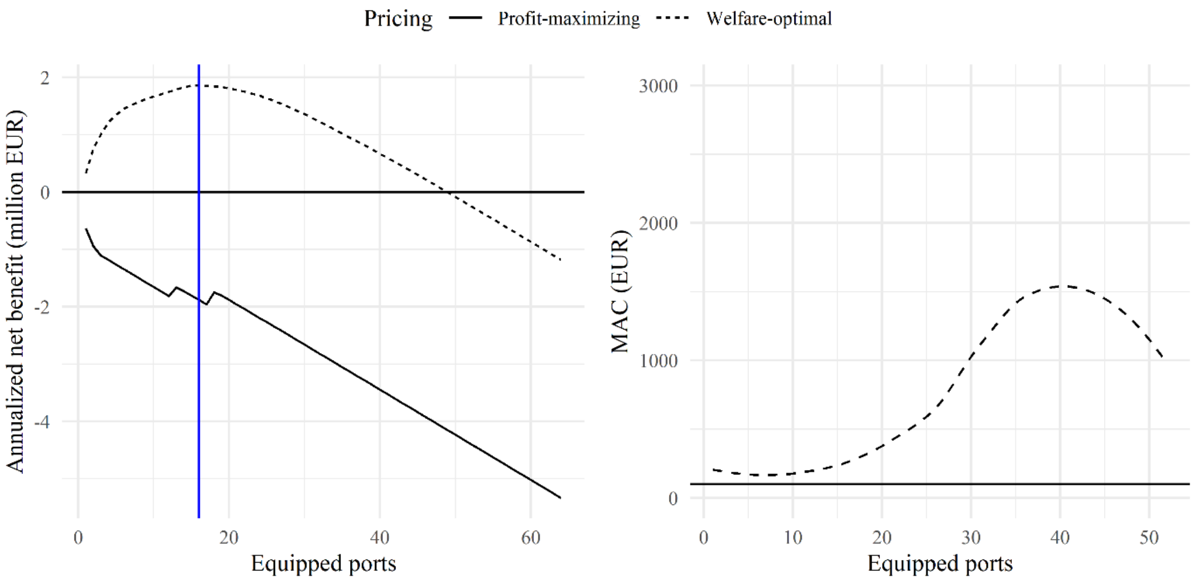

Figure 2 - Tanker segment: Annualized net benefit (left panel) and marginal abatement cost (MAC) per ton of CO2 (right panel), for a range of investment scenarios. Blue vertical line in left panel illustrates the extent of shore power deployment which is most profitable in terms of net social benefits (under welfare-maximizing pricing). Black horizontal line in right panel is drawn at EUR 100, which is the per-ton CO2-valuation applied.

The results for general cargo ships, illustrated in Figure 3, show a similar picture as for bulk carriers. Deployment of shore power in a very small network of ports (a network size of 3 ports is found to be optimal) can be motivated based on positive net benefits, but this result quickly turns negative as larger network sizes are considered. The profit-maximizing pricing scenario shows that no level of deployment would yield positive net benefits. The right-hand panel shows that the marginal abatement cost of CO_2 is above the applied valuation over the entire range of considered deployment.

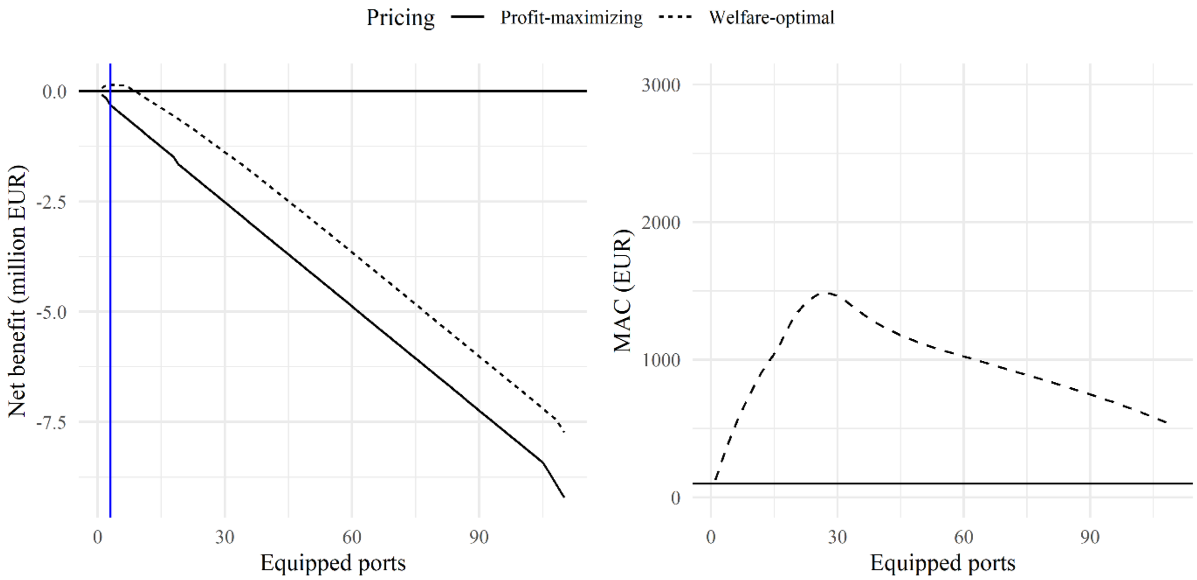

Figure 3 – General cargo segment: Annualized net benefit (left panel) and marginal abatement cost (MAC) per ton of CO2 (right panel), for a range of investment scenarios. Blue vertical line in left panel illustrates the extent of shore power deployment which is most profitable in terms of net social benefits (under welfare-maximizing pricing). Black horizontal line in right panel is drawn at EUR 100, which is the per-ton CO2-valuation applied.

The results for container ships are also calculated and visualized in Figure 4 to provide a reference for comparison with the non-liner segments considered above. The results show a stark difference compared with the other three segments. For container ships, a network-wide deployment of shore power is found to lead to positive net benefits, regardless of whether welfare-optimal or profit-maximizing charging is applied (though there are significant welfare losses associated with the latter). The results also show that the level of deployment which maximizes net benefits is to invest in shore power in 14, or roughly half, of the ports in the network. The right-hand panel shows that investing in shore power (up until roughly the optimal level of deployment) can be motivated on the basis of cost-efficiently reducing CO_2-emissions.

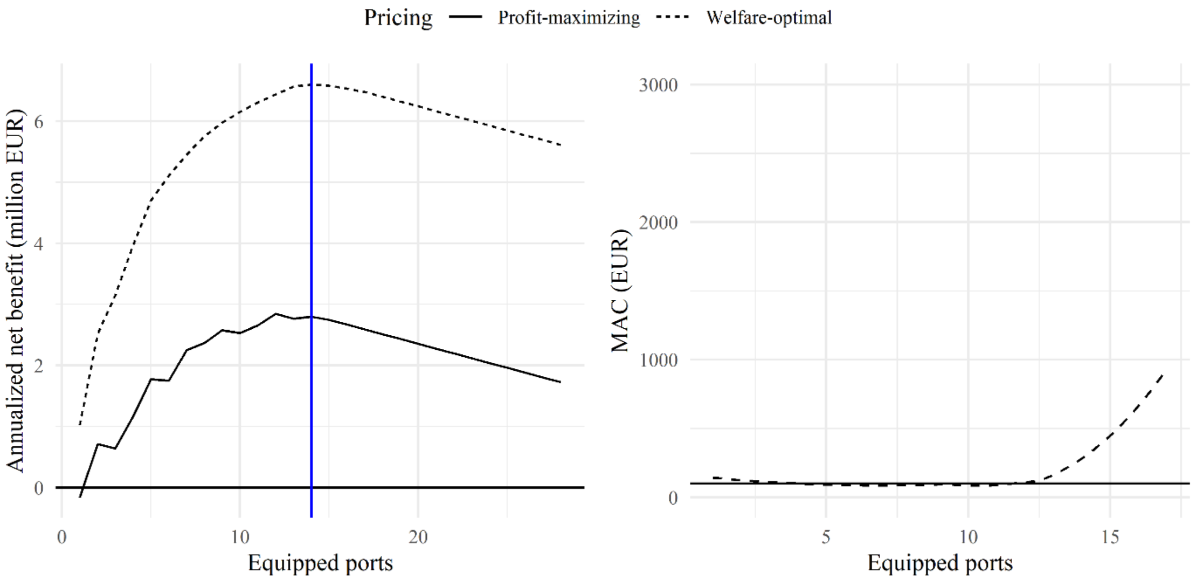

Figure 4 – Container segment: Annualized net benefit (left panel) and marginal abatement cost (MAC) per ton of CO2 (right panel), for a range of investment scenarios. Blue vertical line in left panel illustrates the extent of shore power deployment which is most profitable in terms of net social benefits (under welfare-maximizing pricing). Black horizontal line in right panel is drawn at EUR 100, which is the per-ton CO2-valuation applied.

5.2 Socioeconomic appraisal of optimal investment packages

Table 3 shows a summarized breakdown of costs and benefits for the optimal deployment scenarios shown above. A number of points are worth noting about the results. Firstly, the private benefit in terms of reduced energy costs for ships is smaller than both the value of reduced CO_2 emissions and the value of reduced air pollution in all cases. The value of reduced air pollution is found to lead to larger benefits than those related to abated CO_2. Given the low degree of external cost internalization in shipping, none of the investment packages are profitable solely due to reduced costs for shipowners.

Secondly, for all segments, positive net benefits are found when assuming welfare-optimal pricing, meaning that the optimal investment packages yield positive value for society in relation to the costs of investment. Among the three non-liner segments of interest, the net benefit cost ratio (NBCR) is similar and ranging from 0.29 for the general cargo segment to 0.45 for the tanker segment. This is however in stark contrast to the results provided for the container shipping segment, where investment in roughly half of the container port network is associated with a NBCR of 1.64. This result highlights that the regularity and stability of flows in container shipping provide a solid case for shore power solutions.

A third point to note about the cost benefit analysis in Table 3 is the differences under the different pricing strategies. For all three segments of primary interest except bulk carriers, a negative access charge is required in order to incentivize a level of uptake large enough to generate larger benefits than costs. This result highlights the importance of shipowner incentives when deciding on shore power deployment in ports. As shown by the results, the rate of external cost internalization (100 percent in the case of optimal access charges and 0 percent in the case of profit-maximizing charges) makes the difference between shore power deployment being socioeconomically viable or not.

Increased tax revenues are very modest in relation to other benefits, accounting for less than one percent of net benefits in all segments. This is due to the current tax reduction, which leaves shore power electricity subject to a very low tax rate.

Table 3 – Cost benefit analysis of optimal shore power deployment per segment & under different access pricing. Values express annualized benefits and costs in thousand euros unless otherwise stated.

	Bulk carriers	***Tankers***	***General cargo***	***Container***
Welfare-optimal pricing				
Optimal number of equipped ports	3	16	3	14
Energy cost savings for ships at berth	136	1 012	109	1 721
Value of CO2 emissions reduction	282	2 105	226	3 579
Value of air pollution reduction	432	3 224	347	5 483
Investment costs, ports	-472	-2 125	-314	-1 259
Investment costs, shipowners	-141	-2 054	-199	-2 771
Operational and maintenance costs	-38	-327	-21	-198
Tax revenues increase	3	25	3	43
Net benefit	*200*	*1 860*	*150*	*6 597*
NBCR	*0.33*	*0.45*	*0.29*	*1.64*
Profit-maximizing pricing				
Optimal number of equipped ports	3	0	0	12
Energy cost savings for ships at berth	96	0	0	709
Value of CO2 emissions reduction	200	0	0	1 475
Value of air pollution reduction	306	0	0	2 259
Investment costs, ports	-472	0	0	-1 102
Investment costs, shipowners	-57	0	0	-434
Operational and maintenance costs	-27	0	0	80
Tax revenues increase	2	0	0	18
Net benefit	*49*	*0*	*0*	*2 845*
NBCR	*0.09*	*N/A*	*N/A*	*1.85*

5.3 Sensitivity analyses

The parameters used in the main analysis above are uncertain. The spot price difference between grid electricity and marine fuel is a crucial variable that is subject to variance over time. Given that there is correlation in energy prices, there is some stability in the price differential. However, idiosyncratic shocks to either energy market can increase or reduce this differential significantly. In our first sensitivity analysis, we test the robustness of results to a doubling of the electricity spot price faced by ships while holding the price of marine fuel constant. This represents a significant shock to the profitability of shore power and is also a way to test the impact of the current shore power tax reduction on the socioeconomic viability of shore power deployment. Removing the current tax reduction would in practice represent almost a doubling of electricity spot prices faced by ships in Sweden.

Another point of uncertainty concerns costs of investment in shore power. As previously mentioned, there is a significant degree of variation in landside investment costs depending on preexisting conditions in the port. For ships, the main analysis has used the upper estimates from GloMEEP, in order to reduce the risk of underestimating ship investment costs. However, since relatively few vessels in the segment have actually undergone shore power retrofitting there is a lack of empirical evidence which motivates sensitivity analysis. In our second sensitivity scenario, we increase the assumed costs per berth investment and per ship investment by 50 percent.

The valuation of external effects represents a crucial point of uncertainty since the majority of benefits are related to reduced emissions to air. In the main analysis, we have used a CO_2 valuation equal to that suggested in the European Commission’s (van Essen et al. 2019) handbook on the external costs of transport. In transport appraisal in Sweden, a significantly higher rate is used, equivalent to roughly EUR 670 per ton. This is more than six times the rate used in the main analysis. We apply it as a third sensitivity analysis to study the effect of higher CO_2 valuation on the socioeconomic profitability of shore power investment.

Scenario 1: Higher electricity cost

The results from the first sensitivity analysis shows that for the tanker, general cargo and container segments, the socioeconomic profitability of shore power investment is robust to significantly higher electricity spot prices. However, the optimal level of deployment under welfare-maximizing access pricing is lower than in the main analysis and under the assumption of profit-maximizing pricing, no level of shore power deployment is found to be profitable. For the bulk carrier segment, no deployment is found to be profitable, regardless of pricing.

Scenario 2: Higher investment cost

Similar to the previous scenario, the second sensitivity analysis shows that significantly increased investment costs for shipowners and ports also hampers the potential for shore power investments to be profitable. The results show that shore power provision is only profitable for the tanker and container segments and for tankers this result only holds under the assumption of welfare-optimal pricing.

Scenario 3: Higher CO_2 valuation

As expected, the application of a significantly higher carbon valuation results in the optimal deployment of shore power being larger than in the main analysis. In all cases (except the tanker and general cargo segments under profit-maximizing pricing), the calculated optimal extent of investment and the associated net benefits are larger. There remains, however, a significant gap between the net benefits achieved under either pricing model, which illustrates the welfare losses to be expected from profit-maximizing access pricing.

Table 4 – Summarizing values from three sensitivity analyses per segment & under different access pricing.

	Bulk carriers	***Tankers***	***General cargo***	***Container***
Sensitivity analysis 1 - Higher spot price				
Welfare-optimal pricing				
Optimal number of equipped ports	0	7	2	13
NBCR	N/A	0.07	0.06	1.03
Profit-maximizing pricing				
Optimal number of equipped ports	0	0	0	0
NBCR	N/A	N/A	N/A	N/A
Sensitivity analysis 2 - Higher investment cost				
Welfare-optimal pricing				
Optimal number of equipped ports	0	9	0	13
NBCR	N/A	0.03	N/A	1.01
Profit-maximizing pricing				
Optimal number of equipped ports	0	0	0	9
NBCR	N/A	N/A	N/A	0.23
Sensitivity analysis 3 – Higher CO_2 valuation				
Welfare-optimal pricing				
Optimal number of equipped ports	8	32	37	17
NBCR	1.88	1.89	0.65	5.06
Profit-maximizing pricing				
Optimal number of equipped ports	3	0	0	15
NBCR	2.26	N/A	N/A	6.47

6. Concluding remarks

The results of this study are an indication that investment in shore power can be worthwhile and improve welfare also when aimed at non-liner (tramp) shipping segments. This result is however subject to several caveats. First, it appears that network-wide deployment of shore power is far from cost-efficient for the studied segments (bulk carriers, tankers and general cargo ships). Instead, the results imply that smaller investments focused on a few key ports to form a core network of shore power access is optimal. The optimal extent of shore power investment varies by segment. By contrast, the results for container ships show that the socio-economic profitability of investment in this segment is much more robust.

Second, the results show that pricing matters greatly for whether investments in shore power lead to realized benefits. Depending on how access to shore power is priced once available, the analysis in this study shows that uptake and consequently emissions reduction can be expected to vary greatly.

Importantly, the study finds that in many segments and scenarios, some form of compensation to shipowners, e.g. in the form of negative access prices, are needed to realize positive net benefits of shore power investments. An implication of this result is that simply mandating that ports invest in the provision of shore power, or co-funding investment costs of providing shore power, may not be enough if there are not sufficient monetary incentives for shipowners to take up the technology. A recommendation of this work is that future appraisal and support policies of shore power plans should be explicit about how user pricing is to be set. It is also recommendable to consider whether and how ports' pricing of shore power access can be restricted.

Third, the welfare-optimal charges assumed in this study can be compared to a shipowner subsidy to incentivize uptake. Such subsidies to internalize the benefits of non-fossil power use could be replaced with internalizing taxes on maritime fuel. Subsidies are assumed in this paper since taxes are not decided at the level of any decision maker in the analysis. Increased internalization of shipping's external costs through the proposed EU "Fit for 55"-package can be expected to achieve a similar result as assumed welfare-optimal subsidies if such policies fully internalize benefits of switching to shore power.

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Appendix 1: Modelled optimal networks for shore-power deployment per segment

In order to provide some further detail to the results described in section 5, Table 5 below details which ports make up the optimal shore power networks as found by our modelling. It should be noted that the results may be sensitive to input parameters and the use of historical data for future projections and therefore the listed suggestions from the model should be interpreted with caution. However, the ranked ordering of ports across different pricing assumptions and sensitivity analyses tends to be robust.

The ranked ordering and inclusion of ports in various segments broadly correlate with the number of calls per segment in the listed ports. Busy ports with a high frequency of returning vessels are good candidates for yielding positive modelled net benefits of shore power. However, network effects also play a role in the sense that ports with a high frequency of traffic to/from a port where shore power is profitable is also likely to be modelled as having positive net benefits of shore power.

Table 5 - Ports included in optimal deployment scenarios (assuming welfare-maximizing access pricing) for the included shipping segments.

Order of investment	***Bulk carriers***	***Tankers***	***General cargo***	***Container***
1	Slite	Göteborg	Luleå	Göteborg
2	Degerhamn	Brofjorden	Storugns	Helsingborg
3	Stockholm	Malmö	Oxelösund	Norrköping
4		Nynäshamn		Gävle
5		Norrköping		Stockholm
6		Västerås		Halmstad
7		Stockholm		Tunadal
8		Trelleborg		Åhus
9		Gävle		Holmsund
10		Kalmar		Malmö
11		Södertälje		Varberg
12		Sundsvall		Södertälje
13		Karlshamn		Piteå
14		Helsingborg		Oxelösund
15		Halmstad		
16		Karlskrona		