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ORIGINAL ARTICLE

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Cold ironing: modelling the interdependence of terminals and vessels in their choice of suitable systems

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Abstract

Cold ironing has the potential to reduce the impact of ship exhausts in densely populated areas. However, especially for tankers, the implementation of this concept is almost non-existent. Still, these vessels have a relatively high port energy use, despite relatively short port visits, as they provide power to both pumps and inert gas systems during unloading and loading. A key factor in the reluctance, besides the fact that a sparkless connection is required, is the lack of a standard and the uncertainty from both tanker owners visiting a berth and terminal owners on which shore power systems to apply. This paper investigates the interdependency between ship and terminal owner choices for systems and establishes the overall most economical solution. Cold ironing was reviewed to identify existing systems and solutions and analyse the tanker fleet and terminals. The insights were combined in an integrated economic model consisting of two sub-models; one relating terminal decisions to a cold ironing price and one establishing the vessel side costs and savings. By using fuel price as an input and acceptance rates (for both terminals and vessels) for cold ironing systems as key variables to determine. The models have been used to identify the potential of cold ironing for shortsea and parcel tankers against different fuel prices and % of fleet and terminals that have shore power equipment. In all cases, shore power was not economical, which was caused by the high costs of the fixed costs of electricity, due to the high powers required. Interesting avenues for further research would be to increase the individuality of the model using e.g. an agent based model. Also extending the model with a battery pack on the terminal to allow for peak-shaving could lead to much lower costs and higher economic potential.

Keywords: Cold ironing, Emission reduction, Port strategy, Ship owner

Introduction

Ports form the pinnacles of international trade, goods are received, recombined and loaded on all modes of transport, from large oceangoing vessels to small delivery trucks, with trains and inland barges in between. All this important economic activity unfortunately also has a downside. These port operations have an impact on the environment. Especially shipping with their large engines and heavy fuel oils is seen as a major contributor, albeit the exact impact is still under debate (Eyring et al. 2010; Stolz et al. 2021;

UN 2017; Viana et al. 2014). The fact that ports tend to be located close to densely populated areas and the impact of emissions such as SO_x (Sulfur Oxides), NO_x (Nitrogen Oxides) and specifically particulate matter (PM) has a distinct local character, increases the impact of port operations compared to sailing (Gillingham and Huang 2020; Tian et al. 2013; Winkel et al. 2016). Absolute reductions in the range of 10–15% can be accomplished by converting from auxiliary engines to electricity provided from the quayside. The local benefits could be even larger as electricity could be generated outside of densely populated areas and become increasingly sustainable.

Therefore, it is logical that both local, national and international governing bodies are searching for ways to increase the use of shore power by ships calling at their ports (Commission 2020; Rotterdam 2020; Union 2019; Winkel et al. 2016). This has already led to an increasing number of ferries and cruise vessels adopting shore power, as well as LNG (Liquified Natural Gas) tankers, even for visits of only a couple of hours (D'Agostino et al. 2021; Karakatsanis 2021; Osses et al. 2022). Also, container vessels' use of shore power is on the rise (Zis 2019). However, bulk vessels, which make up most of the fleet, have not yet been converted (Clarkson 2021). Especially liquid bulk vessels berthing in a port pose a complex situation, due to high energy needs and strict safety regulations, due to the risk of fires and explosions. Therefore, this paper investigates the potential costs and benefits of converting (part of) the liquid bulk fleet to shore power.

Currently, there is only one operational shore power system for liquid bulk vessels globally. This shore power system, located in Long Beach, California, was designed in 2007 and was operational in 2009 (Nagel et al. 2007). It is suited for one particular vessel type, the BP Alaska class, connected by three 6.6 kV cables at the aft side of the vessel using its provision crane. An extra pier was constructed to house the cable system in Long Beach. Most importantly, the system has been operating without incidents for over 10 years, proving that tankers' shore power is achievable.

However, some of the choices made for this dedicated service might need to be reconsidered if more liquid bulk vessels are connected to the system. An overview of the shore power system is given in “Onshore power supply” section. In “Methodology” section the methodology and model will be discussed, while in “Case study” section, the model will be applied to a case study. In “Case study” section conclusions and recommendations are given.

Onshore power supply

In essence, a shore power system consists of five parts; The shoreside energy supply, the shore power connection point, the cable management system, the shipside connection point and the shipside energy system (Ballini and Bozzo 2015; Gamette et al. 2010; Røed 2018; Sciberras et al. 2015; Tarnapowicz and German-Galkin 2018; Trellevik 2018). Therefore, in this section, the system function and alternative implementations will be discussed for each system part and followed by the knowledge gap.

Shoreside energy supply

The shoreside energy supply is the substation in which the high-voltage grid power is converted to the correct voltage and frequency. In most countries, the frequency is 50 Hz, except for several countries in the Americas (Tarnapowicz and German-Galkin

2018), on the other hand, ships mostly operate at 60 Hz (Clarkson 2021; Røed 2018). Furthermore, the shore to ship power connection is standardised by IEC 80,005 and consists of multiple cables with a voltage of either 11 or 6.6 kV. The number of cables is dependent on the total power consumption while connected (Røed 2018). In general, tankers will be using two to three 6.6 kV cables, which means the substation will convert the 10–15 kV high-voltage into this. As the exact location of the substation has a limited impact on the final solution, only the costs will be considered for this project.

Besides the cost of the conversion station, the emission benefits of shore power are highly dependent on the country's energy mix in which the vessel is connected, as the well to tank emissions will need to be taken into account as well, instead of only the tank to wake emissions. The average share of green power in the electricity mix for the European Union (EU) is still quite low. The EU is striving for a share of green electricity of at least 49%, and therefore the impact will improve in the future (Knopf et al. 2015). This will be further discussed in the case study.

Cable management system

The cable management system (CMS) placement on the terminal side has been seen in the long beach implementation and the normative guidelines from the International Electrotechnical Commission (IEC) (Gamette et al. 2010; Røed 2018). In Fig. 1, several examples of terminal design are presented; the slender jetty (left to images) is found predominantly. Besides these, for loading (dirty) tankers, a buoy is not uncommon as well. In many cases, the jetties are already quite full, possibly requiring additional jetties to be constructed, impacting the investments significantly. Furthermore, the location of the CMS concerning the ship is important because that will define the distance from which the cable must be transported to the ship's receiving point. Both aspects are a clear indication that the specifics of the design of the involved terminal should be considered as input for the calculations.

When considering the CMS, two aspects are to be considered. First, tankers, due to the explosive nature of their cargos, have explosive atmospheres (ATEX, from the French atmospheres explosible) zones defined. If the CMS would be within the ATEX zones, cables, systems, and storage need to be ATEX-certified (EU 2014). Secondly, 6.6 kV cables are both thick and heavy, requiring consideration of the minimum bending radius

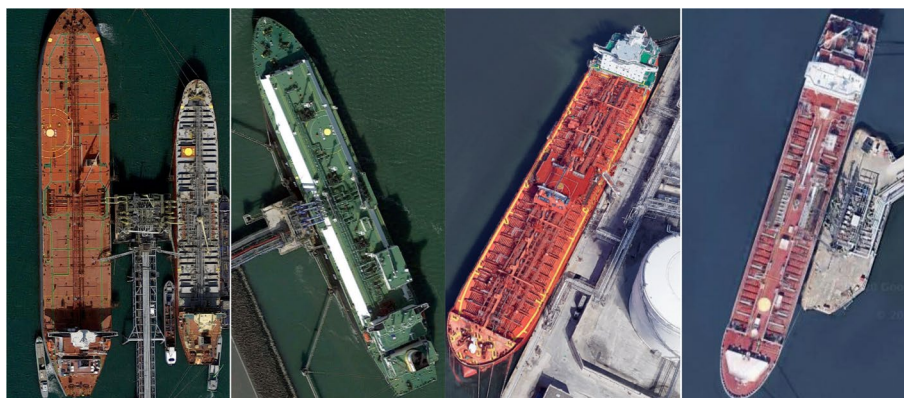


Fig. 1 Examples of tanker mooring situations to illustrate the issue of selecting a connection point. *Source:* Google Maps

of the cables and the mechanical tension in the cable (Gamette et al. 2010; Røed 2018). Therefore dedicated systems are often required to make the connection to the ship. As only one commercial system exists today, a workshop with experts from the port, shipping companies and terminal operators was organised resulting in five different principles for the connection that will be discussed below shortly.

Reel on top

This is an elevated inerted container with a reel inside. The connection is made midships, requiring extensive ATEX compliance measures. The hose handling crane also has to be present on the vessel, besides connections on the portside and starboard, including a galvanised cable tray to run the cable to the aft part of the ship to the shipside system. This system currently only exists as a design and has not yet been operational. Alternatively, the connection could be made to the aft-ship, using the provision crane instead of the hose handling crane. This would reduce the amount of cabling on the ship and place the connection outside of the ATEX zone. Furthermore, it is assumed that only one connection point is required due to the limited range of the provision crane.

Loading arm

The key difference between a loading arm and the reel on top is that the crane is located on the terminal. The cables could be run through pipes to comply with the ATEX requirements, similar to the vapour return lines. The same cable and connection requirements for the reel on top are required.

Floater

A self-propelled floater could connect the cable to the aft side of the vessel. Then, if available, the provision crane could get the cable from the floater to the vessel, if available. A key advantage is that the aft side of the vessel is usually not an ATEX zone, requiring less strict measures concerning the connection. Also, the shipside energy system is located aft, resulting in a much shorter connection distance. Finally, in this situation, only one connection point would be required. Due to the floater, this concept is quite flexible, though it currently only exists as a concept and has not been developed or used.

Crane and cable reel

This is the system of choice for most ferries and cruise ships already receiving shore power. The system consists of a shore-based crane and cable reel connecting to the aft side of the vessel. As these ships predominantly dock at quaysides, this system is quite flexible. Placed on a jetty, however, the range of the system is limited due to the immobility of the crane. As the connection is aft, the benefit of one connection point, a short distance to the shipside system and no ATEX requirements remain.

To summarise, the five systems are compared in Table 1.

Shipside connection point

As mentioned in the previous sub-section, there are two connection points for the ship: midships and aft. Considering that most ports have jetties for loading/unloading, the midship connection is more flexible when considering significant variation in ship

sizes, as it remains in the same position. On the other hand, the aft connection requires more flexibility from the system as due to the midship connection, the location will vary with the size of the ship; see also the leftmost image in Fig. 1. Considering the impact of the ATEX zone (EU 2014), the aft ship connection is outside of that and could be a more standard connection. Midships an ATEX-compliant connection for the power is required, which, to the knowledge of the authors, is not yet available for multiple 6.6 kV connections. This research will assume that such a connection is technically feasible as several compliant ideas and concepts can be generated, e.g. a connection in an inert gas box.

Shipside energy system

The liquid bulk sector comprises several vessels and sizes. Furthermore, besides diesel generators, also boilers are used onboard liquid bulk carriers. The steam generated by the boilers is used both to heat the cargo and to drive the cargo pumps (Clarkson 2021; UNCTAD 2021). In Table 2 an overview is presented of these key qualities for different subsectors of the liquid bulk industry. The extensive range and size differences are clear. As terminals tend to differentiate primarily by cargo, but not by the size of ships they receive (Rotterdam 2020). For instance, a storage terminal may receive a large vessel unloading its cargo, but this could later be picked up by much smaller shorter-range vessels for delivery to customers.

Especially for the larger vessels (see Table 2), the use of boilers can be recognized by the low installed power to deadweight (DWT) ratio, especially with oil tankers. This will be impacting the effectiveness of shore power. A mid-life conversion to electrical boilers is not economic; besides, there are no electrical boilers of that size available. This would make large oil and gas tankers not the most likely candidates to lead the shore power transition. It would require new boiler developments and a slow transition by installing them in newly built ships. On the other hand, although the impact per call of these large vessels is high, these vessels sail long-distance contracts, and their total time spent in port is relatively low. Furthermore, the smaller number of vessels further strengthens this when compared to the number of ships for the shorter ranges. This could indicate that focussing on the smaller ships could reduce port emissions more than focussing on the larger vessels and will be investigated further in the case study.

The shipside system consists of a connection, a cable from the connection to the engine room, a transformer to convert the 6.6 kV to the onboard voltage and a breaker. Although, not an additional system, the current does need to be synchronised between ship and shore (both at the connection and disconnection) to prevent any blackouts (Innes and Monios 2018; Sciberras et al. 2015). As these systems are required independent of the connection type, their costs will be assessed in this study, but not the impact on space or other factors such as energy loss due to running a longer cable to the midship connection.

To better understand the needs for the shore power system, the demand from the shipside is further investigated. First of all, it is essential to realise that the power demand from the ship is not constant.

Figure 2, the average load compared to the installed electrical power is presented for a Suezmax tanker. The relatively low values can be explained by the fact that, in general,

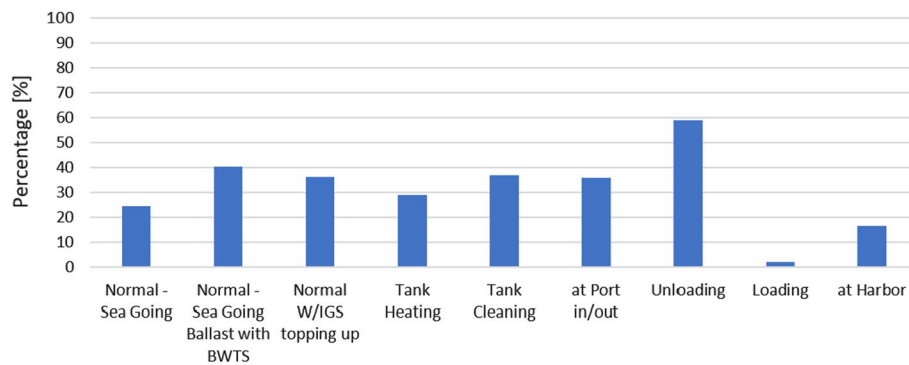


Fig. 2 Electric load analysis of a Suezmax tanker, averages per operation

Table 1 Overview of cable management systems and qualities. *Source:* Authors

	Status	ATEX	Ship impact	Flexibility
Reel midship	Concept	Yes	Large	High
Reel Aft	Proven	No	Medium	Low
Loading Arm	Concept	Yes	Medium	High
Floater	Concept	No	Medium	High
Crane and Reel	Proven	No	Low	Low

Table 2 Overview of key ship type attributes for shore power. *Source:* Authors, based on information from (Clarkson 2021; UNCTAD 2021)

Sizetype	DWT (kDWT)	Length (m)	Installed E-power (kW)	# of Diesel-generators	Cargo pumps	# of ships
<i>Oil</i>						
Shortsea	0–20	64–130	600	3	Electrical	4204
MR	30–55	180–184	2,700	3	Electrical	2092
LR1	70–80	228–229	2,700	3	Steam	431
Aframax	100–120	239–250	2,400	3	Steam	1004
Suezmax	150–165	274–277	2,850	3	Steam	476
VLCC	295–320	330–336	3,750	3	Steam	771
<i>Gas</i>						
Shortsea	0–15	67–119	900	2	Elec/steam	840
Handymax	15–30	154–180	2,950	3	SteamElec/steam	255
MR	45–60	225–230	3900	3	Steam	317
LR2	70–100	281–298	10,350	4	Steam	524
<i>Chemical</i>						
Shortsea	0–10	66–120	950	3	Electrical	1756
Parcel	10–20	122–148	1,650	3	Electrical	1167
MR	25–50	159–184	2,950	3	Electrical	509
<i>Special</i>						
Shortsea	0–10	32–100	250	–	–	338

one more diesel generator set is installed than necessary from the operational profile. This is done both for safety and to allow one generator to be maintained while operating the vessel. In the case of the Suezmax, three generators are installed where two are needed. From the specific case in Fig. 2, the processes of tank heating, tank cleaning, unloading, loading, and harbour could be supported by shore power. However, this can only be supported as long as the ship is berthed and not every cargo requires tank heating.

Knowledge gap

Based on the discussion in the previous sub-sections, the key choice in a shore power system is the connection point and system. However, as demonstrated, the adaptations required for this could vary with both terminal designs and calling vessel particulars. Also, the presence of boilers could impact the achievable reduction for the more significant ship types. Finally, preference for a midship or aft located connection differs also depending on the view. A shipowner would prefer aft as it reduces his investment but potentially increases that of the terminal. Vice versa, the terminal would prefer midships to reduce its investment, but this increases the costs for the shipowner. On both sides, a sufficient number of installations is required to keep the costs manageable, so enough ports provide shore power and enough vessels ask for shore power.

To the authors' knowledge, no research addressing this dilemma has been published so far. Hence, this research aims to establish the impact of such choice both for owner and terminal and identify the most likely group of ships to start the shore power implementation. The remainder of this paper discusses the methodology in "Onshore power supply" section and the case study results in "Methodology" section; finally, it draws some conclusions in "Case study" section.

Methodology

In order to decide the best choice of CMS, a strategic economic model was developed to investigate both the ship and terminal side and the conditions under which shore power would be economically feasible. An overview of this model is provided in Fig. 3. The model contains three parts; an input port for the considered ships, indicated on the left. As the model is strategic, total yearly power demand is determined, rather than dealing with loading and unloading separately. Of course, by changing the input one could investigate loading and unloading terminals separately if desired. The second part is the terminal input on the right. This consists of the terminal layout, which relates to the investment costs, the yearly calls, and the country-related data concerning electricity costs and emissions.

The middle part forms the actual model, containing terminal and shipside calculations. It starts with the CMS choice, which impacts the investment costs for both applications. This is input for the levelized costs of energy (LCOE); The LCOE for the ship is determined by the difference in costs for fuel and electricity from the terminal per MWh multiplied by the total amount of shore power energy used. This depends on the ship's properties as well as on the number of times shore power is available. Similarly, the LCOE of the terminal depends on the difference for which they offer the shore power energy and the costs of this energy (including system costs) times the amount of

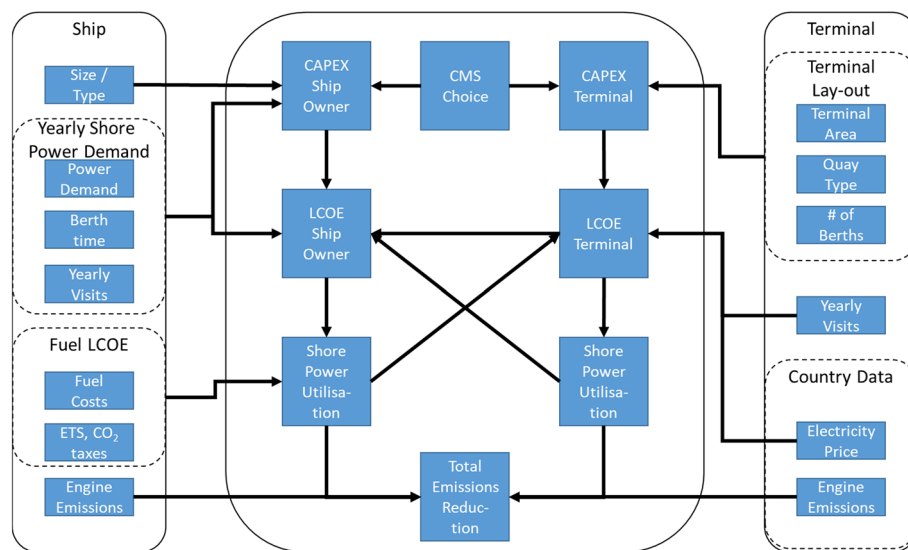


Fig. 3 Cold ironing integrated ship-terminal model overview. *Source:* Authors

shorepower sold. This is dependent on the number of vessels able to receive shorepower and their demands for power during a visit. At this point the issue becomes entangled as for the shipowner, the total demand depends on the ship type and the number of terminals offering shore power. In contrast, for the terminal, the demand depends on the ship type and the number of ships with shore power. Higher implementations lead to lower costs in both cases as capital expenditure (CAPEX) can be shared over more energy demand. In this initial investigation, manual variations will be used to investigate both sides of the model; however, as the model is set up modular, in the future optimisation could be introduced for this part, and other parts could be detailed further as well.

Although our focus will be on applying the model to the liquid bulk sector, in essence, the model could be applied to any type of operation. The key differences are in the ship and terminal input. In general, more power is required during loading, unloading and tank washing and the quay types differ, increasing expenses for the installation. A detailed discussion of the model formulations will follow in “[Shoreside Energy Supply](#)” section for the ship and “[Cable Management System](#)” section for the terminal, while the input will be discussed in the case study (“[Methodology](#)” section).

Shipside model

As shown in Fig. 3, the shipside consists of four parts: the investment, the LCOE, which consists of costs and benefits (deferred tax), the utilisation decision, and the emissions. The costs for installing a shore power system are based upon the costs for standard shore power equipment that is required and the costs for a specific CMS. These costs vary per ship type (ship). The standard shore power equipment consists of a transformer, breaker and adjustments on the electrical equipment as discussed in “[Shipside energy system](#)” section.

The total cost of ownership is shown in Eq. 1 and is expressed in euro. It depends on the installation costs of the breaker and transformer, the connection to the switchboard

and that to the shorepower cable. The annualised costs are based on this and calculated with Eq. 2, using the capital recovery factor concept (Zakeri and Syri 2015) to consider the time value of money.

$$TCC_{ship} = C_{breaker}(\max(P_{Ship,n})) + C_{trafo}(\max(P_{Ship,n})) + C_{adjust} + C_{CMSs,x}[\text{€}] \tag{1}$$

where TCC_{ship} = total capital expenditure for this ship type (ship) [€], $C_{breaker}$ = costs for a breaker on board as a function of maximum discharge power [€], $C_{transfo}$ = costs for a transformer on board as a function of maximum discharge power [€], C_{adjust} = costs for the adjustment of the ship’s switchboard to use shore power as a power source [€], $C_{CMSs,x}$ = costs of all CMS choice related adaptations for that CMS type (x) on the ship-side [€], $P_{Ship,n}$ = The electrical power demand for the ship type during operation n [MW].

$$C_{cap,ship} = \frac{TCC_{ship} + CRC_{ship}}{T} \left[\frac{\text{€}}{\text{year}} \right] \tag{2}$$

where $C_{cap,ship}$ = annualised value of the total capital cost [€/year], CRC_{ship} = Capital Recovery Costs as a function of interest rate of investment and the actual investment [€], T = lifetime of the system (20) [years].

The operational expenses (Eq. 3) are primarily related to the electricity costs from the Terminal model side. Additionally, a connection fee would be expected for connecting the vessel for each call. Furthermore, there is extra maintenance for the shore power systems. Currently, the included operations are loading, unloading and washing, as the latter is mixed with the unloading operations but requires less power. For the calculation, the total power demand per call is an input (Eq. 4). This can be derived from specifying for each operation the power and time required. The time includes both that of the operation and the additional time of connecting and disconnecting the shore power. Finally, the operational profile of this ship is crucial as it could include terminals with and without shore power. This is an output of the terminal model and impacts the number of operations with shore power (Eq. 5).

$$OPEX_{ship} = TSP_{ship} * C_{el,term} + C_{maint} + \sum_{n=1}^3 ops_{n,ship} * C_{con,n} \left[\frac{\text{€}}{\text{year}} \right] \tag{3}$$

where $OPEX_{ship}$ = Operational expenses for the CMS per shiptype [€/year], $C_{el,term}$ = terminal (term) dependent costs of shore power electricity [€/MWh], C_{maint} = shipside CMS maintenance costs [€/year], $C_{con,n}$ = operation based connection costs [€].

$$TSP_{ship} = \sum_{n=1}^3 P_{ship,n} * ops_{n,ship} * (t_{ship,n} - 2 * t_x) \left[\frac{\text{MWh}}{\text{year}} \right] \tag{4}$$

where TSP_{ship} = the ship’s total yearly shore power demand [MWh/year], $Utility_{term}$ = if the terminal has shore power [-] (output from the terminal model), $t_{ship,n}$ = the average time at berth for operation n for the chosen ship type [h], t_x = the time for connecting CMS x [hr].

$$ops_{n,ship} = \frac{\sum_{term=1}^p Utility_{term} * vis_{term,n,ship}}{\sum_{term=1}^p vis_{term,n,ship}} \tag{5}$$

where $ops_{n,ship}$ = the yearly amount of operation n with shore power for that ship type [1/year], $Utility_{term}$ = the presence of economically viable shore power equipment for that terminal type [-], $Vis_{term,n,ship}$ = operational profile, number of yearly calls to a specific terminal for operation n by that ship type [-].

The benefits for the shipowner (Eq. 6) consist of the fuel costs saved and the reduced maintenance costs for the auxiliary engines. As the fuel costs are customarily given in euro per ton, these will have to be converted to a euro per energy price, using the specific fuel consumption and the engine efficiency. Although, in reality, these values depend on the load on the generator, this is currently deemed too detailed, and fixed values will be used within this investigation, as the impact would be minor.

$$REV_{ship} = \frac{C_{fuel} * \frac{SFC}{1000}}{\eta_{AE}} * TSP_{ship} + \frac{\sum_{n=1}^3 ops_{n,ship} * (t_{ship,n} - 2 * t_x) * C_{AE_{maint}}}{24 * 365} \left[\frac{\text{€}}{\text{year}} \right] \tag{6}$$

where REV_{ship} = revenue(or expense reduction) for the ship type when using shore power [€/year].

C_{fuel} = fuel price for MGO [€/ton], SFC = this is the specific fuel consumption taken as 210 [kg/MWh] (Klein Woud and Stapersma 2003; Rao et al. 2015), η_{AE} = auxiliary engine efficiency set to 0.95 [-] (Wartsila 2020), $C_{AE_{maint}}$ = auxiliary Engine maintenance costs [€/h].

The utilisation of shore power is economically dependent on the benefits exceeding the costs, which is depicted in Eq. 7. It should be realised that even within a ship type, different operational profiles could lead to different fractions of terminals providing shore power. This fraction, in turn, depends on the vessels with shore power connections visiting it.

$$Utility_{ship} = \begin{cases} 1, & REV_{ship} - OPEX_{ship} - C_{cap,ship} \geq 0 \\ 0, & REV_{ship} - OPEX_{ship} - C_{cap,ship} < 0 \end{cases} \tag{7}$$

$Utility_{ship}$ = the presence of economically viable shore power equipment for that ship type.

The last element on the shipside model is the emission reduction, as this module also requires input from the terminal side model, which will be discussed in “[Cable Management System](#)” section below.

Terminal side model

The same elements as the shipside model are present within the terminal side model and will be discussed in the same order. The CAPEX of the terminal is a function of the design power of the shore power installation, the structure of the quays, the layout of the terminal and the amount of cable management systems installed at the terminal. The total cost of ownership is calculated in euros in Eq. 8. Like the shipside, the total investment is converted to yearly costs, including a capital recovery factor (Eq. 9).

$$\begin{aligned}
 TCC_{term} = & C_{grid}(P_{Cap,term}) + C_{Ehouse}(P_{Cap,term}) \\
 & + C_{cables} * d_{term} + n_{CMS} * C_{CMS_{t,x,term}} \\
 & + C_{Eng}(P_{Cap,term}) [€]
 \end{aligned}
 \tag{8}$$

where TCC_{term} = total capital expenditure for this terminal type (term) [€], $P_{cap,term}$ = capacity of the installation installed [MW], C_{grid} = costs of the grid connection [€], C_{Ehouse} = costs of the E-house with transformers and frequency converters [€], C_{cables} = costs of the HV cable connections between source, E-house and CMS [€/m], d_{term} = total distance of cable to be installed on the terminal [m], n_{CMS} = number of quays connected [-], $C_{CMS_{t,x,term}}$ = terminal side CMS costs for system x considering the terminal quayside situation [€], C_{Eng} = engineering costs, a function of installed capacity [€].

$$C_{cap,term} = \frac{TCC_{term} + CRC_{term}}{T} \left[\frac{€}{year} \right]
 \tag{9}$$

where $C_{cap,term}$ = annualised value of the total capital cost [€/year], CRC_{term} = Capital Recovery Costs as a function of interest rate of investment and the actual investment [€], T = lifetime of the system (20) [years].

The operational costs consist of the electricity costs and the maintenance of the system (Eq. 12). The electricity costs consist of the connection and electricity costs directly related to the energy used. Different elements are included within the connection costs; the connection itself, costs based on the capacity installed (Eq. 11) and a cost based on the actual maximum capacity used each month. These costs promote a stable electricity demand, which means that irregular usage, such as the shore power system, could be expensive due to short high power demands. However, to calculate these costs, the power demand will need to be determined first (Eq. 10), which in turn relies on the operational profile of the vessel calling. As in this case, the power demand differs per vessel type. This part is included in Eq. 10. As discussed in “Introduction” section, especially the CMS located aft might not support all vessels calling at the terminal; the final factor corrects this in the equation. Similarly, when connected aft, the vessel needs to berth in the right direction; based on discussions with harbour pilots this is possible 95% of the events.

$$\begin{aligned}
 TSP_{term} = & \sum_{n=1}^3 \sum_{ship=1}^q Utility_{ship} * vis_{term,n,ship} * P_{ship,n} \\
 & * (t_{ship,n} - 2 * t_x) * f_{CMS,x} * f_{dir,x} \left[\frac{MWh}{year} \right]
 \end{aligned}
 \tag{10}$$

where TSP_{term} = the total energy demand of all ships calling at the terminal [MWh/year], $f_{CMS,x}$ = factor for the fraction of ships able to use the CMS installed [-], $f_{dir,x}$ = fraction of ships berthing in the assigned direction, only relevant for CMS located aft [-]

$$P_{Cap,term} = \max_n \left(\frac{\sum_{ship=1}^q Utility_{ship} * vis_{term,n,ship} * P_{ship,n}}{\sum_{ship=1}^q vis_{term,n,ship}} \right) * n_{CMS} * f_{var} [MW] \tag{11}$$

f_{var} = factor to compensate for the variation in Capacity demand set by the user [-]

$$OPEX_{term} = C_{E-fixed} + C_{E-Cap} * P_{Cap,term} + C_{E-MCap} * P_{MCap,term} + C_{E-del} * TSP_{term} + C_{maint} [€/year] \tag{12}$$

where $OPEX_{term}$ = total operational expenses for the terminal [€/year], $C_{E-fixed}$ = total fixed transport and connection costs [€/year], C_{E-Cap} = installed capacity related costs [€/ (MW*yr)], C_{E-MCap} = maximum capacity used related costs [€/ (MW*yr)], $P_{Mcap,Term}$ = average of monthly maximum capacities used [MW], C_{E-del} = costs of electricity [€/MWh], C_{maint} = total maintenance cost of the systems on the terminal [€/year].

The benefit to the terminal is the income from selling the electricity to the ships using shore power at that terminal. This is provided in Eq. 13. Equation 13 is followed by the utilisation equation (Eq. 14), identical to the one for ships but with a subscript related to terminals.

$$REV_{term} = TSP_{term} * C_{el,term} \tag{13}$$

where REV_{term} = revenue for the terminal when providing shore power [€/year].

$$Utility_{term} = \begin{cases} 1, & REV_{term} - OPEX_{term} - C_{cap,term} \geq 0 \\ 0, & REV_{term} - OPEX_{term} - C_{cap,term} < 0 \end{cases} \tag{14}$$

Finally, the emission reductions are calculated in the last step of the model (Eq. 15). The basic equation is provided below for 1 ship in one port. However, all visits could be added together to calculate ships' and terminals' system's total contribution to shore power.

$$\Delta Em_{i,ship,term} = Utility_{ship} * P_{ship,n} * (t_{ship,n} - 2 * t_x) * (f_{MGO,i} - f_{E,term,i}) [g/MWh] \tag{15}$$

where $\Delta Em_{i,ship,term}$ = the particular (i) emission savings for a particular port call by a particular ship [g/MWh], $f_{MGO,i}$ = Amount of emission i emitted for 1 MWh [g/MWh] of MGO. $f_{E,term,i}$ = Amount of emission i emitted for 1 MWh using electricity from the country of the terminal [g/MWh].

Model validation was implemented in Excel, and an initial case study was applied to investigate the working and the created results. This case study will be discussed next.

Case study

The case study is focused on investigating a potential pilot group for the application of shore power within liquid bulk. In order to select a suitable group, the overall yearly shore power demand for each group mentioned in Table 2 was estimated for the Port

of Rotterdam (PoR). PoR was selected as it is the largest liquid bulk hub in Europe and receives many vessels yearly. Based on this first comparison, both VLCCs (Very Large Crude Carrier) and chemical tankers showed potential. However, as the VLCCs use boilers that cannot be replaced by shore power yet and have a limited number of visits per year, it was assumed that the short range chemical tankers (shortsea and parcel from Table 2) would have a higher potential for success. An additional benefit of this sub-selection is that all vessels in the group are similar in length, eliminating CMS aft's restrictions.

Within this sector, a group of 45 vessels that called regularly at the PoR (at least one in five port calls) was selected. When investigating their voyage history, it was discovered that 52.3% of their port calls were concentrated in five ports: Rotterdam, Antwerp, Le Havre-Rouen-Paris Ports (HAROPA), Teesport, and Southampton. Therefore, for the case study, it is assumed that these ports all offer shore power, and all other ports will not. A jetty quay is assumed for each terminal as this is the most common and most costly to adapt for shore power.

After investigating 10 terminals within the PoR, the selected vessels would form 17–79% of the calls to that terminal. However, one dedicated shore power berth seems reasonable, with each terminal operating between 2 and 7 berths. Therefore, it would result in 60–130% occupancy (possible vessel berth time/1 berth) compared to the average for that terminal and, as > 100% is not possible, two berths for the two most bustling terminals. Therefore, the situation with one and two berths with a CMS will be considered for the case study.

The key input parameters are shortly discussed in [Shipside Model](#) section, while the results are presented in [Terminal side model](#) section. The final 3.3 section will draw the case study related conclusions.

Model input

The vessel input is presented in Table 3 below. All data used is, as much as possible, from actual measurements such as the statistics maintained by the port. Where this is not possible, the case other reputed sources were used. Finally, for aspects that not even the port maintained statistics for the best possible source was used (e.g. an estimation of operators or actual (confidential) quotations). The input variable(s), their value, the source and a remark if required are provided. To start with the vessel side CMS costs, although a system aft should be cheaper, the lack of cranes on shortsea chemical tankers is increasing the costs in this case. As can be seen due to the limited data availability, some key parameters had to be estimated (with their base given in the remarks). These were considered fixed independent of the vessel type. A key variable is energy use, as only data was available on larger vessels' loading, unloading and tank washing operations. The fractions of total installed power were used for a weighted average based on times for each operation. Therefore, the values in Table 3 are based on this fraction in combination with the average installed power based on the vessel data as available in Clarkson (2021). As a result, the terminal call times are based on the average for loading and unloading as registered for each vessel type by the PoR. Finally, to run the models independently, both electrical and Marine Gas Oil (MGO) costs are also used as input in the model.

In Table 4, due to data confidentiality, the costs were not split directly according to the model layout but separated by costs related to a CMS and the fixed costs for an installation provided shore power. Therefore, the costs for a CMS also include, for instance, a transformer in the E-house and a filter plus any additional cabling. It is clear that from a terminal perspective, the fixed costs have the most impact and offering 1 or 2 CMS points will increase costs by 50%. The differences between the CMS systems are much smaller. However, it should be realised that for an aft connection a new jetty might be required, adding about 250,000 € to the total. In order to use the terminal model separately, the fraction of ships that are shore power ready can be set by the user.

Furthermore, the example terminal is somewhat larger, which is beneficial to the implementation of shore power. The terminal receives about 5% of the vessel calls in these categories, although there are 98 terminals identified. However, only 33 receive one ship per month or more.

The maximum ship demand is estimated at 15% above the average unloading demand, as in this case, ships do vary slightly. In the case where there are two or more CMS installed, the weighted averages based on the calls are taken as the maximum per CMS. This is a lot lower due to the majority of ships being much smaller. Hence the basic installation for one or two CMS can still be kept at 2.0 MW. Furthermore, as E-houses do not contain many rotating and mechanical parts, maintenance is assumed to be relatively cheap. Finally, the other costs are taken from an industrial power information leaflet (STEDIN 2021).

Finally, to allow the emissions to be calculated, the emissions of MGO and Electricity have to be provided within the model. In Table 5 these inputs are presented, the reduction achieved by switching to shore power is clear for all emissions. This impact will only increase with the increase of the contribution of clean energy to our energy mix. Using this input, the ship model and the terminal model will be run independently to study the impact of the key variables. This will be discussed in the next section.

Results of the pilot study

Applying the current Dutch electricity emissions to the idealistic case, the overall savings are 27% on CO₂, 59% on NO_x, 19% on SO_x and 55% on PM, which is quite a significant reduction for the port area. This would warrant further investigation of shore power in general, but especially for short-range tankers. Their contributions to the port area are significant and local emissions do have the most impact on the health of the people living there. On the global scale, the yearly vessel emissions reduction is much smaller (e.g. about 2% for CO₂).

Within the results first, the shipside model is investigated. In Fig. 4, the installation of each CMS system is considered, and an equilibrium fuel price (y-axis) is calculated for each fraction of called terminals with shore power (x-axis). A couple of observations can be made. First, in none of the cases is shore power economically viable against the mentioned fuel price of 500 €/ton. Under the current assumptions, the fuel price needs to be 635 €/ton to even out electricity costs. Only above this price can a part of the investments be regained. A fuel price of about 700–750 €/ton would make shore power viable in this case. This is an increase of about 50%, which might seem a lot, but would be about equal to an Emission Trading System (ETS) CO₂ price

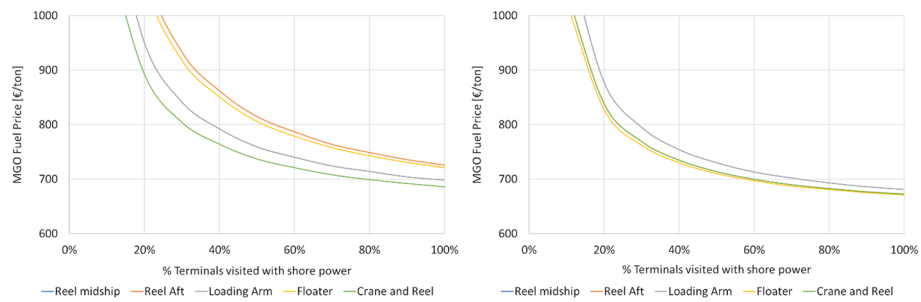


Fig. 4 Break-even fuel price in function of terminals with shore power (Shortsea left, Parcel right)

Table 3 Overview of shipside related input for the model. *Source:* Authors

Variable	Shortsea	Parcel	Source	Remark
TCC _{ship}	382,500 €	426,500 €	PoR confidential quotations, hence only totals are presented	Reel midship
	533,000 €	336,500 €		Reel Aft
	382,500 €	426,500 €		Loading arm
	533,000 €	336,500 €		Floater
	293,000 €	336,500 €		Crane and Reel
Utility _{term}	52,3%	Port calls data PoR	Based on the assumption that the 5 most called ports offer Shore power	
ops _{n,ship}	(52.3*105)	(52.3*70)	Port call data PoR	
P _{Ship,n}	565 kW	990 kW	(Clarkson 2021)	Time-weighted average of loading and unloading
(t _{ship,n} - t _x)	26.5 h	32.0 h	Port visit data PoR	
C _{maint}	1000 €/year	Estimate	Based on regular maintenance estimations from experts	
C _{con,n}	100 €/call	Estimate	Based on discussion with experts	
C _{el,term}	140 €/MWh	Calculated	This is a starting value that can be adjusted to terminal model results, ranging between 120–150 €/MWh	
C _{fuel}	500 €/ton	(Bunkerworld 2020)	Average of a range from 300–700 €/ton	
C _{AEmaint}	1.80 €/h	(Trellevik 2018)		

of about 75 €/ton, which according to Psaraftis et al. (2021) is not unrealistic in the near future if a reduction is to be achieved. Furthermore, a rather high availability of terminals with shore power is required as below 40% availability, all options require a fuel price above 750 €/ton.

Second, it is more difficult to pay back the investment for the smaller shortsea tanker (Fig. 4, left side) compared to the parcel tanker (Fig. 4, right side). This is a disadvantage, as these smaller vessels make more calls to the terminal. Thirdly, the CMS options overlap largely on the ship side for the parcel tanker, as a provision crane is assumed available, which is not the case for the shortsea vessel. Finally, the floater is the best option for the parcel tanker, followed closely by the crane and reel (aft) and the reel aft, as this vessel has a provision crane aft. For the shortsea tanker, the crane and reel aft CMS option is the best option. However, the floater and reel aft score as the worst options as a crane will need to be installed on the vessel solely for this purpose.

Table 4 Overview of terminal side related input for the model. *Source:* Authors

Variable	Terminal	Source	Remark
$C_{CMS,x,term}$	668,000 €	PoR confidential quotations, hence only totals are presented	Reel midship
	713,500 €		Reel Aft
	734,000 €		Loading Arm
	694,500 €		Floater
	845,500 €		Crane and Reel
$C_{grid} + C_{Ehouse} + C_{cables} + C_{Eng}$	1,590,500 €	PoR confidential quotations, hence only totals are presented	2,0 MW is assumed so the system is ready for a maximum of 2 connected CMS
$f_{CMS,x}$	1	User input	This is related to the chosen CMS, however in this case all ships can share the aft located connections
$f_{dir,x}$	0.95	Estimate	Based on an estimate of pilots 5% are not able to dock in the requested direction
$Utility_{ship}$	0.25	User input	This is a starting value (based on port calls), that can be adjusted to the shipside model results, ranging between 0.00–1.00
$Vis_{term,n,ship}$	200 per year	Port calls data PoR	Chemical – Shortsea
	38 per year		Chemical—Parcel
$P_{ship,n}$	1.15*1155 kW	(Clarkson 2021)	1 CMS installed (Max average plus 15%)
	1.15*660 kW		2 CMS installed (Weighted average plus 15%)
C_{maint}	2,000 €/year + 2,000 €/year per CMS	Estimate	Based on quotations
$C_{E-fixed}$	2760 €/year	(STEDIN 2021)	
$C_{E-Cap} + C_{E-MCap}$	52.50 €/(MW*year)	(STEDIN 2021)	
C_{E-del}	8.20 €/MWh	(STEDIN 2021)	

Figure 5 selecting each option for the CMS as input, the required shore power sell-

Table 5 Overview of emissions per kWh for fuel and electricity. *Source:* (CEDelft 2020)

Emission	MGO	Dutch Electricity
CO ₂	705	390
NO _x	7.7	0.223
SO _x	0.27	0.182
PM	0.25	0.025

ing price (per MWh) can be calculated for different fractions of ships able to receive shore power. It is pretty unrealistic to assume that all 238 calls can be full-filled with one jetty. The time at the jetty would already be over 280 days and this does not include the manoeuvring to and from the jetty. This means that the right-side graph should be used for situations with over 50% shore power connections. In that case, only when all visitors have a shore power request would the price of shore power fall below the 140 €/MWh that was assumed to be sufficient for the shipside model. The actual cost will most likely be higher based on these outcomes

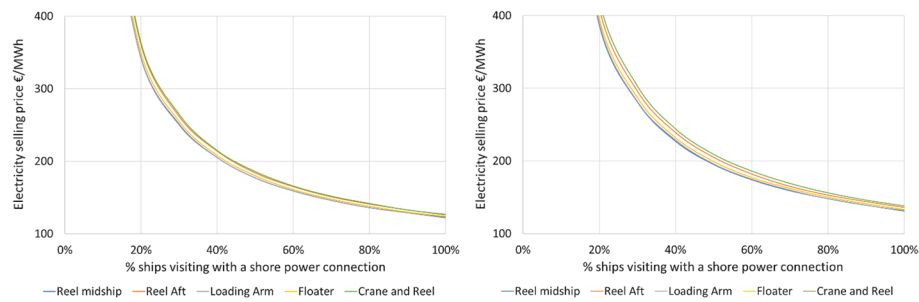


Fig. 5 Break-even shore power price in function of ships with shore power (1 CMS left, 2 CMS right). A similar set of graphs can be created for the port side. See *Source*: Authors

On the other hand, the impact of different CMS options is very limited; the cost associated with the shore power choice is much higher than the choice for a CMS. These are valuable first outcomes as for the shipowners, the impact indeed is significant, and a choice for a system could thus be based primarily on the shipside impact.

Practical implications

The key issue for the shore power on the terminal side is the vessels' irregular and relatively short use of shore power. Even in the two CMS case, with 100% of the ships requesting shore power, the total energy usage is only 4,300 MWh. This is about a quarter of the capacity of the connection ($365 \cdot 24 \cdot 2 = 17.5$ k MWh). Hence the fixed costs for the investment and the grid connection are not regained efficiently, increasing the price of shore power beyond an economically viable level. With full utilisation of the connection, going to the unrealistic fraction of 4.0 for the ships with shore power, the shore power costs would drop to about 85 €/MWh. Allowing for that price in the ship model with a crane and reel aft, shore power would also be profitable for the more expensive shortsea vessel using an MGO price of 500 €/ton in the described case of 52% of the terminals offering it (see Fig. 4). A discussion with network providers on the rates charged and a further investigation into energy storage on the terminal to lower the required connection and equipment capacity should result in a more economically attractive shore power price.

Another key observation from the case study is that shore power generally requires a high level of compliance on both sides to be feasible. Ships require sufficient terminals, and terminals require sufficient ships (at least 50% of the calls). This makes shore power for tankers challenging to implement as it is not easy to find viable pilots. However, if the Port of Rotterdam in this case, is keen on shore power, establishing contacts with other ports frequently called by the targeted fleet shore power could be realised also for tankers. A more detailed study of routings and contracts could reveal a set of such terminals that, together with the vessels operating between them, would be able to form such a seeding point to the benefit of all.

Conclusions and recommendations

Although a relatively basic case study was performed with the model as a first test case, it already created valuable insights into the key difficulties of implementing shore power for liquid bulk carriers. The issue of requiring a large group of adaptors and the issue of

the significant under-usage of the grid connection and equipment, lead to high overhead costs.

The current model has several limitations, in our case study, all vessels were assumed to be identical, within a specific group. This is of course not realistic as vessels are often one-offs. Similarly, for the terminal side, the timing of visits of vessels with and without shore power was not investigated, this could increase the unavailability of shore power for vessels requesting it and this would decrease the fraction, making the current results slightly optimistic. Furthermore, the current focus did not yet include a solution on how to deal with boilers, as their power usage would be even larger, increasing the system costs on both sides further. This means that although developed for all tankers, the larger tankers will only develop a limited shorepower demand and still use fossil fuel to operate their boilers.

From an academic standpoint, the current model could be extended with more vessel types and terminals, creating an intricate network of shipping routes and solving the complex equilibrium for various scenarios once reprogrammed in a more suitable language. Furthermore, the identification of a solver would be required for the more complex instances of the model, where multiple vessel and terminal types, or even unique ones, can be introduced, and the equilibrium between costs and adaptation can be solved.

Finally the increase in the validity of the data used for the shore power system. The values are in the right ballpark, but more accurate values would undoubtedly improve the outcome validity and support further model use for policy discussions and evaluations with both ship and terminal owners.

These limitations also result in a number of recommendations for future research. Two key directions are considered relevant. The first is the extension of the model to incorporate a network of terminals and represent a heterogeneous fleet of vessels, all with individual properties. This would increase the insight into the adoption and especially the order adoption will take, starting with the most suitable trades and vessels, but with each following terminal with shore power, more vessels and trades become relevant and a snowball effect is expected to occur. Perhaps an agent based model could be used for this, the model in this paper could function as a basis for agent choices in that case.

The second recommendation is to implement the use of innovations in the delivery of electricity such as battery packs. These would reduce the peaks in power demand, resulting in a significant reduction in electricity costs. The research in this area may be able to contribute to an update of the model and lead to a more positive view of shorepower for tankers.

Abbreviations

ATEX	Atmosphere explosible (explosive atmosphere)
CAPEX	Capital expenditure
CMS	Cable management system
DWT	Deadweight
EU	European Union
HAROPA	Le Havre-Rouen-Paris joint port operations
IEC	International Electrotechnical Commission
LCEO	Levelized costs of energy
LNG	Liquefied natural gas
MGO	Marine gas oil
NO _x	Nitrogen oxides

PM	Particulate matter
PoR	Port of Rotterdam
SO _x	Sulfur oxides
VLCC	Very large crude carrier

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Author contributions

The research was executed by JW under the Supervision of JP. The paper was written by JP, with support and input from JW. All authors read and approved the final manuscript.

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Availability of data and materials

As a large part of the dataset are proprietary to the PoR, we can only disclose the input as provided within the paper.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

PoR as involved third party have given their consent for publication.

Competing interests

We declare to have no competing interest.

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