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Cold ironing and onshore generation for airborne emission reductions in ports

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Abstract

Cold ironing (or onshore power supply) addresses airborne emissions while ships are berthed in port. By providing the electrical power demands from shoreside electricity, the onboard auxiliary generators can be switched off for a locally emission-free solution. The net emissions will of course be dependent on the actual shoreside electricity mix but reductions can be realised in most cases. This study looks at the various electrical configurations available for cold ironing of berthed vessels. Shoreside generation using LNG as an alternative fuel is also considered as a complement to cold ironing. This provides the possibility of hybridised solutions combining power supply from the grid or from clean, onsite generators. Using real data from an operational European port, the various cold ironing configurations are modelled and optimal trade-off solutions were identified. This is achieved by considering the reduction of emissions and minimisation of component costs as a multi-objective nonlinear optimisation problem. Results show that CO₂ emissions can be reduced by up to 40% by using cold ironing, while the use of LNG shore generation can reduce the Sulphur and particulate emissions in port to extremely low levels.

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Keywords

Cold ironing, onshore power supply, air pollution, optimisation algorithm, shoreside power, LNG generation.

Introduction

The carriage of freight by sea is one of the more efficient means of transportation in terms of CO₂ emissions per tonne of cargo and distance transported.¹ The time at sea of a merchant vessel generally constitutes the largest period of operation compared to the berthed period.² Yet the period of charging/discharging cargo while the vessel is berthed occurs close to habitation centres and thus any resultant emissions will have an immediate (and apparent) impact.

Environmental legislation provides an impetus to reduce emissions throughout vessels' operations with Directive 2012/33/EU of the European Parliament placing limits on the Sulphur content of fuel used onboard ships operating in member states' waters. In this directive, a vessel which turns off its engines while berthed and uses shoreside electricity is exempt from the Sulphur limitation, and onshore power supply is encouraged as an alternative solution for reducing emissions in member states' ports.³ This complements IMO's Annex VI directive which similarly limits the Sulphur content of fuel, with distinctions being made for different waters and Emission Control Areas (ECAs).⁴

Onshore power supply (or Cold Ironing as it is often referred to) involves the provision of the ships' electrical demands while berthed from the port shoreside supply, avoiding the need to run the onboard auxiliary generator sets for a locally emission-free solution. In providing power to a number of berths, a number of electrical configurations are possible. This study considers the various available options and identifies the solutions giving the best overall compromises between emission reduction and system cost. Data from a collaborating port in North-West Spain is used for this representative study, using operational

profiles and corresponding berthed vessels' load demands to determine the optimal cold ironing/shore generation configurations for this particular scenario.

Finally shoreside generation using alternative fuel is considered as a complement to shore power supply, potentially providing hybrid solutions which can address some of the issues associated with the implementation of cold ironing. LNG-fuelled shoreside generators were considered alongside power provision from the grid, giving the possibility of lowering the demand from the utility supply. By considering a combined shoreside generation/cold ironing system, the number of possible configurations is increased; hence a non-linear optimisation algorithm was used to identify the best solutions in terms of capital costs and emission reductions in a multi-objective optimisation study.

Cold ironing overview

Cold ironing presents an engineering challenge in the connection of two otherwise separate systems. The matching of the port electricity supply to that of the consumer (i.e. the onboard ship electricity supply) in terms of voltage and frequency is critical to a seamless and easy connection. Ships are installed with a variety of onboard electric systems, depending on their type and individual design. A survey of Roll-On/Roll-Off (RoRo) vessels visiting the case port showed the distribution of ship voltage and frequency shown in Figure 1. Additionally, larger vessels (such as cruise ships) can also use medium voltages (>1 kV) and high voltages (6.6 kV and 11 kV) due to their higher electrical demands. The power demands of various vessel types are also highly variable, with powers ranging from hundreds of kilowatts for small vessels to tens of megawatts for cruise ships. Such a high power demand can present a constraint on the shore supply network, requiring new substations⁵⁻⁷ or the upgrading of the transformers, switchgear, cables, etc.

Figure 1. Shipboard power systems prevalence (a) onboard voltage, and (b) frequency of onboard ship supply.

Voltage transformation is relatively straightforward by means of transformers, but frequency conversion requires the use of solid state frequency converters which greatly increase system cost and complexity. These converters utilise power electronics to rectify the incoming supply to an intermediate DC link before this is modulated to the appropriate frequency by the output inverter.⁸

Standardisation

In summer 2012, a joint ISO/IEC/IEEE standard was published which addresses the shore connection of ships and establishes the fundamental requirements for worldwide cold ironing.⁶ Prior to standardisation, all cold ironing implementations were bespoke systems which were adopted on a case-by-case basis based on a joint undertaking between port and ship operators. This was mainly restricted to vessels on regular visits to the same berth (such as ferries).

Clearly, having a uniform system (as promoted by standardisation) presents numerous advantages in that compatible ships can easily connect to compliant port facilities. Figure 2 illustrates the basic requirements of a cold ironing connection as defined by IEC/ISO/IEEE 80005-1,⁶ highlighting the components required onshore and on board. On the shoreside, a frequency converter is required to convert the utility supply frequency to that demanded by the berthed vessel (50 Hz to 60 Hz or vice-versa) while a shore transformer provides galvanic isolation as well as voltage step-up/down, as necessary. IEC/ISO/IEEE 80005-1 specifies a shore transformer for each berth connection, but frequency converters can power multiple berths depending on the network topology. Each berth's ship-to-shore connection is provided at a berthside switchboard, which includes the circuit breakers necessary to protect the ship-to-shore connecting cable. The protection system should also include an interlocked earthing switch which solidly earths the cable when it is disconnected. This rapidly discharges any dangerous electric charge stored in the cable's effective capacitance to ensure safe handling.⁹

At the ship end of the connecting cable, a matching shore connection switchboard provides protection to the rest of the downstream system. Linking these two switchboards is the ship-to-shore connection cable, together with an optical pilot interlock (located within the cable itself). This interlock provides a safety mechanism which actively monitors the integrity of the connection, tripping the protective devices if any break in continuity is detected. If the ship uses a non-standard voltage (i.e. not 6.6/11 kV)⁶ an additional onboard transformer is required to match the voltage levels. Finally, the ship receiving switchboard (typically part of the vessel's main switchboard) provides the necessary interlocking with the ship's generation system and handles the synchronisation necessary to perform a switchover from onboard generation to the shore supply.

Figure 2. Generic cold ironing standard requirements.

Cold ironing topologies

Extending the system of Figure 2 to cater for multiple berths or connections provides a number of different connection options and topologies. Each of these gives different operational characteristics with respect to efficiency, cost and operational flexibility.¹⁰ These configurations differ mainly in the placement and ratings of the frequency converter/s and transformers leading to the three different topologies described in the next sections. In this study, a five berth existing RoRo terminal in Spain is considered, with existing trenching and hook-up points linking the berths and central substation as shown in Figure 3.

Figure 3. Overview of port layout.

Distributed cold ironing topology

In a straightforward extension of the system of Figure 2, a distributed topology replicates the complete system for each berth with a frequency converter and transformer for each berth/connection. This gives greatest flexibility and redundancy but also the highest component count, especially in terms of power electronic converters. Figure 4 shows the distributed topology for the five-berth port considered in this study.

Figure 4. Distributed cold ironing topology.

Centralised cold ironing topology

In contrast, Figure 5 illustrates a centralised topology, where a single frequency converter is centrally located, which together with a double busbar arrangement permits either 50 Hz or 60 Hz to be supplied to a berth as required. By taking into account the expected load diversity (since not all ships are likely to demand the same frequency at the same time) the power electronic converter can be smaller in size than the total combined load.

Figure 5. Centralised cold ironing topology.

DC distribution cold ironing topology

As a hybrid between the two previous topologies, a DC distribution topology (Figure 6) mirrors industrial multi-stage process drive systems (such as paper making or steel mills) by extending the DC link into a DC bus, such that all the inverters share a common DC input and rectifier stage. With a DC distribution, integration with any energy storage devices or alternative energy sources within the harbour is facilitated, as only a DC interface is required. However protection on DC systems is more complex when compared to AC systems (due to the lack of natural current zero) especially at higher voltages.

Figure 6. DC distribution topology.

Some of the attributes of the three topologies are comparatively ranked in Table 1. Resilience refers to the ability of the cold ironing system to ride-through a single converter fault. In the distributed case, each connection is independent of the rest; hence a fault on any converter will not affect any other. In the centralised case, a fault on the centrally located converter will result in loss of power to all the 60Hz berths, but leaving the rest unaffected. Conversely, any fault in the rectifier stage in the DC distribution topology will shut down the whole system while a fault on one of the inverters will shut down its associated berth with no possibility of bypass operation. Table 1 compares the relative merits and attributes of the three topologies, chiefly in terms of installation space and reliability.

Table 1. Comparison of topology attributes.

Attribute	Distributed topology	Centralised topology	DC distribution topology
Resilience	High	Less	Least
Component count	High	Least	Less
Berth footprint	High	Least	Less

Shore distribution network modelling

In order to provide comparisons between the topologies described above, a parametric energy-centric model of the shoreside networks was developed. This permits various configurations and designs to be explored and examined within an automated script such that optimal designs can be identified. The comparison is to be performed on an efficiency basis; therefore circuit models which account for the various losses in the components are sufficient for modelling purposes. This also accounts for additional losses due to harmonics introduced by the switching converters, causing an increase in the RMS value of the current as well as additional magnetic losses in transformers. The transformer and frequency converter models are described in more detail in the next two sections, since these account for the majority of losses in the shore network.

Transformer model

The transformer equivalent circuit of Figure 7(a) gives the equivalent circuit of a real transformer, which can be simplified by referring all elements to the primary side giving the referred equivalent circuit shown in Figure 7(b).¹¹ In this equivalent circuit, the magnetisation branch (X_m in parallel with R_c) appears at the primary terminals. This branch accounts for the real power losses in the core (V_p^2/R_c) and the magnetising current ($-jV_p/X_m$). R_{eq} and X_{eq} represent the combined primary and secondary winding resistance and reactance, respectively, referred to the primary. The actual transformer secondary output voltage (V_s) is

given by $V_s = V'_s/a$ where a is the transformer voltage ratio. Similarly the output current of the transformer on the secondary side is $I_s = aI'_s$.

Figure 7. (a) Model of real transformer and (b) approximate equivalent circuit of a transformer referred to the primary side.

The input (primary) current I_p in Figure 7(b) consists of three components: the armature current I'_s , the magnetising current I_{mag} and the current responsible for providing the no-load losses in the core, I_c . The no-load core loss (P_{noload}) is associated with eddy-current and hysteresis losses in the core and is represented by R_c . No load losses are typically considered as fixed losses at 1% of the transformer's kVA rating and do not change with load. The magnetising current (I_{mag}) is typically constant at 4% of rated

current, but lags the supply voltage by 90° . Load losses (P_{ll}) will vary according to the loading on the transformer, and can be classified as the losses due to resistance in the windings (P_{I2R}) and losses due to stray flux linkage (P_{TSL}). These stray losses are caused by flux linkages with other transformer components.

The referred approximate equivalent circuit of Figure 7(b) is valid for the fundamental harmonic frequency. Additional losses are imposed on the transformer due to the non-sinusoidal nature of the actual current flowing through it. This is caused by non-linear loads connected downstream of the transformer drawing non-sinusoidal currents (such as frequency converter). These will result in the total RMS value of the current being greater than the fundamental, leading to additional Ohmic losses in the circuits. Within the magnetic circuit of a transformer, additional losses will occur due to the effect of harmonic currents on the magnetic core. These additional losses due to harmonic effects are quantified according to an estimation procedure defined by IEEE Std. C57.110-2008,¹² and explained in further detail in the Appendix.

Frequency converter

The basic power electronic circuit is shown in Figure 8, with additional associated control algorithms and processing to maintain a 50 Hz or 60 Hz output, as desired. The losses associated with the converter are the switching and conduction losses in the switching devices themselves. Switching losses in the power electronic devices are due to the non-zero current and voltage waveforms during device turn-on and turn-off, while conduction losses are due to effective resistance of the devices while conducting current.

Figure 8. Schematic diagram of frequency converter.

The voltage and current waveforms for a single device are illustrated as Figure 9 together with the corresponding power losses, where V_s is the input voltage appearing across the switch when turned off, I_{on} is the steady state current through the switch and V_{on} is the (small) on-state voltage. The switching losses are given by equation (1). Similarly, equation (2) defines the conduction losses during the on state period (t_{on}).

$$P_s = \frac{1}{2} V_s I_{on} f_s (t_{c(on)} + t_{c(off)}) \quad (1)$$

$$P_{on} = V_{on} I_{on} f_s t_{on} \quad (2)$$

where $t_{c(on)}$ and $t_{c(off)}$ are the turn on and turn off times, respectively, and f_s is the switching frequency.¹³

Figure 9. Device switching waveforms and power loss characteristics: (a) voltage and current waveforms, (b) instantaneous power losses across power electronic device.

With a fixed frequency output, power losses will vary according to the current through the device (i.e. the total load on the inverter). Additional losses are also produced in the passive components associated with

the converter including the DC link capacitor and any filter inductances at the input. Losses in the DC link capacitor are associated with the RMS ripple current flowing through the capacitor, leading to a heating effect due to its equivalent series resistance (ESR). Since the model is required to account for losses in the circuit, a Look Up Table (LUT) of converter efficiency with respect to percentage loading was used.⁸

Emission factors

Airborne emissions are one of the main concerns addressed by the provision of power from shore supplies, especially with respect to the immediate harbour area. This is generally close to human habitation; hence any environmental improvements will have an immediate impact on human health. However cold ironing is not a zero-emission solution; rather energy production is shifted out of the immediate harbour area to generating stations on the national grid. The net resultant emissions will therefore be a function of the generation mix employed in the country of connection.^{7, 14} The consideration of emissions on a national level will therefore reflect national energy policy and strategy, and permits consideration of the environmental impact of cold ironing without requiring detailed regional network information to quantify emissions.

In order to obtain emission factors for each type of fuel used on shore, the electrical energy produced by each type of fuel (in GWh_e) from the Digest of United Kingdom Energy Statistics¹⁵ was correlated with the respective declared CO₂, SO₂ and NO_x emissions for the corresponding year as reported in the UK Greenhouse Gas Inventory.¹⁶ This gives the shoreside emission factors for generated electricity from major generation sources as listed in Table 2. Renewable (solar, wind, photovoltaic and hydroelectric power) and nuclear generation are considered as producing zero airborne emissions during operation.

Table 2. Emission factors for onshore generating stations for various fuel types.

Fuel type	CO ₂ (g/kWh)	NO _x (g/kWh)	SO _x (g/kWh)
Coal	911.6	1.76	1.66
Fuel oil	683.2	2.5	1.78
Natural gas	394	0.26	3.91×10 ⁻³

These emission factors are then combined with generation mix figures published by the International Energy Agency¹⁷ to give the weighted emission factors for generated energy in a number of countries, (Table 3). This clearly shows the influence of the generation mix on the resultant emissions for generated electricity.

Table 3. Weighted emission factors for generated electricity based on generating mix for various countries.

Country	CO ₂ (g/kWh)	NO _x (g/kWh)	SO ₂ (g/kWh)
UK	478.9	0.7	0.5
Spain	331.1	0.5	0.4
France	75.6	0.1	0.1
Germany	478.6	0.9	0.8
Turkey	684.1	1.0	0.8
US	585.4	1.0	0.9
China	762.6	1.5	1.4

This is then compared with emission factors from onboard auxiliary generators in Table 4, which gives the g/kWh of emissions produced by various types of engines running on different fuel types.¹⁸ Transmission and distribution losses in the system must be considered in order to compare emissions at the point of consumption. These losses are available as averaged values,¹⁷ while the final shore network distribution losses must be modelled according to the particular topology and network design used. Comparing Table 3 and Table 4 it is apparent that depending on the generation mix employed, there can be a significant reduction in CO₂ emissions, especially in countries with a high nuclear generating percentage (such as France).¹⁴ NO_x reductions are also very significant across the board. Interestingly, SO₂ margins are much closer in the case of ships using low Sulphur fuel for their auxiliary generators.

Table 4. Emission factors for onboard auxiliary generators.¹⁸

Auxiliary engine type	Fuel type	CO ₂ (g/kWh)	NO _x (g/kWh)	SO ₂ (g/kWh)
Medium Speed Diesel	Marine Gasoil (0.1%)	690	13.9	0.44
	Marine Diesel Oil (1%)	690	13.9	4.3
	Residual Oil	722	14.7	12.3
High Speed Diesel	Marine Gasoil (0.1%)	690	10.9	0.44
	Marine Diesel Oil (1%)	690	10.9	4.3

Shore supply port case study

This study aims to look at the impact of cold ironing on airborne emissions by considering a case port (shown in Figure 3), taking a typical week as an example study. The port consists of a five-berth RoRo terminal in North-West Spain regularly visited by a number of different ships. Over a year, this port has seen over four hundred RoRo visits from about fifty individual vessels ranging in size from 2,000 tonnes to 22,000 tonnes (deadweight). Based on onboard measurements and surveys on several visiting vessels, the onboard electrical demand of vessels while berthed was correlated with the vessels' deadweight to obtain an estimate of the power requirement of ships of a similar type while in port, as shown in Figure 10.

Figure 10. Variation of berthed ship auxiliary power demand with ship size.

From the onboard measurements it was observed that the power demand while berthed is practically constant for the duration of the vessel's stay. With this approximate relation between power and deadweight, it was possible to estimate the average power demands over a typical, representative week (Figure 11) illustrating the power demand for each berth. This representative week is an example of a busy time at the port during the summer period (when the onboard electrical demand is higher due to cooling requirements) and thus provides a more demanding profile for a design study like the one presented in this paper.

Figure 11. Power profiles for case port over a representative week.

In this study, the potential benefits of cold ironing are examined from the perspective of the port operator with the assumption that all vessels visiting the terminal are able to connect to the shore power supply. From the shipowners' point of view however, a number of economic factors need to be taken into account

in order to justify investment in ship to shore technology. These include the frequency of visits and the availability of cold ironing facilities at the various ports being visited, particularly for vessels on regular runs.

Identification of optimal cold ironing configurations

In order to identify the optimal configuration, a search algorithm was used to identify which topology and what component ratings (sizes) give the highest efficiency for this particular scenario, namely the port shown in Figure 3 with the power profiles of Figure 11. However, simply considering a single objective function (minimising losses) will not translate into a realistic and feasible solution, since an oversized system will always be selected to give the lowest overall losses. In order to identify realistic configurations, the consideration of multiple conflicting objectives makes a search algorithm locate a set of optimal *compromise* results which addresses all objectives for the best trade-off solution set.¹⁹⁻²¹ This manifests itself as a non-linear multi-objective optimisation problem, which was solved using a multi-objective Particle Swarm Optimisation algorithm.

Minimising losses in the system (maximising efficiency) reduces the energy required from the supply, thus reducing the generated airborne emissions. For a realistic consideration of the merits of the implementation of cold ironing, this must be balanced against the capital costs involved in setting up the cold ironing system.²² The actual costs are highly specific to the individual cold ironing installation and will vary greatly depending on the need for infrastructural works (such as trenching), disruption to port operations as well as sufficient power availability in the existing substations. A weighted component count approach was therefore adopted which accounts for an installation cost based on the number of components in the system and their type and rating. This permits comparisons to be made between topologies. Each type of component was assigned a per-unit value of cost per kVA of rated power (pu/kVA). As an example, a transformer is assigned a cost value of 1pu/kVA, such that the total (normalised) cost of a system can be estimated by summing up of component count and size.

LNG Shoreside generation

One of the major constraints on cold ironing is the power demand placed on the utility supply by the berthed ships (e.g. the recommended rating for a cruise ship connection is for 16 MVA).⁶ If the existing port infrastructure does not have sufficient spare capacity, additional substations must be constructed and additional incoming feeders might also be necessary, together with the associated protective switchgear, transformers and cabling. This all involves a significant potential additional cost which negatively affects the feasibility of new cold ironing systems.

Reduction of harbour demand by means of energy saving measures can be a way of providing sufficient spare capacity to accommodate extra loads, depending on the actual port power demands and loads, and the required extra power. For a large disparity between power availability and demand, the provision of extra supply would be necessary. In an effort to reduce the load on the utility, an alternative proposal is to provide power by generation within the harbour area using alternative sources.²²

Renewable sources within the harbour serve to improve the generation mix for the localised demand and can be considered within the developed model by adjustment of the generation mix (Table 3). In this work, alternative generation is considered as consisting of generator sets fuelled by Liquefied Natural Gas (LNG). LNG is widely touted as a cleaner alternative to conventional diesel fuels, with extremely low levels of particulate and Sulphur emissions.²³⁻²⁵ This has resulted in an increase in the popularity of LNG as an onboard fuel, reflected in the growth in the number of LNG-fuelled ships, together with an increase in available bunkering facilities worldwide, and wider range of engine offerings by manufacturers.

In this optimisation study, the shoreside generation system was analysed with an LNG-fuelled generator set replacing one or more of the individual berth connections of the cold ironing system as shown in Figure 12. In this case berths 2 and 3 are supplied by LNG generators, while the remaining berths are connected to a distributed cold ironing network. This represents a situation where the benefits of a port with an LNG supply can be exploited by conventionally-fuelled vessels.

Figure 12. Example of combined system with LNG generation for two berths within a distributed cold ironing system.

The different configurations were compared based on their airborne emissions as well as component cost, similar to the cold ironing only scenario described previously. In this case however, the comparison has to be performed on the basis of emission levels instead of the demanded energy since two different sources of power are now available. The cost objective is treated in a similar way to the above analysis, by adopting a per-unit cost per kVA rating of the installation components to provide an objective comparison between configurations. However, in this case the study is further complicated by the fact that the per-unit

cost of the LNG system is highly dependent on the actual infrastructure required (e.g. whether the port already has an LNG bunkering facility or not). The infrastructure costs associated with LNG generation are much less definable compared to those of cold ironing due to the many additional costs that may be incurred apart from the cost of the generator itself. These include the cost of LNG storage, piping, safety requirements, etc. which may vary significantly from one site to another. As a result, the per-unit cost per kVA of the LNG generation system was considered as a further variable, providing sets of results for a number of different LNG system costs.

Results

When a number of equally optimal solutions exist in a particular multi-objective optimisation study, the set of compromise solutions in which different priorities are considered is referred to as a Pareto-set of solutions.¹⁹ The final selection of a preferred solution is then achieved by the user taking into account higher-level information such as engineering judgement. In this study, the search algorithm was run in order to identify Pareto-optimal sets of shore network configurations which minimise emissions while at the same time keeping the component costs to a minimum.

The search space consisted of the rating of each berth, the cold ironing topology (Figures 4 to 6) together with the selection of cold ironing or LNG generation for each particular berth. The objective functions considered were the total CO₂ emissions and the total cost of the resultant system, with a view to minimising each. Similar objective functions can be considered for other emissions. The emission figure was quantified using the model developed in Simulink and the emission factors for the particular country of interest, while the system cost is obtained from a weighted sum according to the selected configuration and ratings as described in previous sections. This was first performed considering a cold ironing system only, before considering additionally the hybrid cold ironing/LNG generation configurations. When cold ironing is considered on its own, it was observed that a centralised cold ironing topology was the most suited for this scenario giving the best compromise between emission reductions and system cost.

Figure 13 shows the results of the configuration search showing the various solutions for a number of different LNG system cost figures. It is clear from the sets of solutions that there is a different bias depending on the relative cost of the LNG system. When the LNG system has a higher per-unit cost than the frequency converter (considered for comparison since it is the highest cost component in the cold ironing system), the optimal solution set consists of a pure cold ironing system, i.e. the study indicates that there will be no advantage by going for an LNG generation system in terms of cost or reduced emissions (the top left corner of Figure 13).

Figure 13. Pareto-optimal configuration objective space for sets of combined LNG/Cold ironing systems.

The picture changes when the specific cost of the LNG system is comparable to, or lower than the specific cost of the frequency converter. In such cases, going for an increasingly LNG-generation dominated system can result in lower total costs, at the expense of higher emissions, when compared with

the cold ironing only configuration (the lower right corner of Figure 13). Table 5 and Table 6 present two different configurations from two of the costs cases considered. These were selected from the set of solutions (corresponding to Figure 13) for each optimal set. Each of the solutions in Figure 13 can be considered as being equally optimal within its own set, with the final selection performed by the user based on engineering judgement.¹⁹

Table 5. Configuration description for LNG system being $\frac{1}{3}$ the frequency converter specific cost.

Configuration	Component ratings (kVA)						Topology	CO ₂ emissions (kg)	SO ₂ emissions (kg)	NO _x emission (kg)	Total cost (normalised cost)
	Berth 1	Berth 2	Berth 3	Berth 4	Berth 5	Central					
Cold ironing	750			900	1050	1350	Centralised				
Shoreside LNG generation		1000	1350				Distributed	23964	10	75	10450

Table 6. Configuration description for LNG system being $\frac{2}{3}$ the frequency converter specific cost.

Configuration	Component ratings (kVA)						Topology	CO ₂ emissions (kg)	SO ₂ emissions (kg)	NO _x emission (kg)	Total cost (normalised cost)
	Berth 1	Berth 2	Berth 3	Berth 4	Berth 5	Central					
Cold ironing		1100	1350		1550	1900	Centralised				
Shoreside LNG generation	650			550			Distributed	21113	18	46	14000

Table 5 describes one particular configuration from the set of results when the specific cost of the LNG system is one-third the specific cost of the frequency converter (in the cold ironing system). With the (significantly) lower per-unit cost of the LNG generation system, there is sufficient benefit in terms of costs to provide a bias towards LNG generating configurations on the Pareto-optimal front at the expense of higher emissions (compared to a purely cold ironing configuration). Conversely with a higher specific

cost for the LNG system, there is no benefit either in terms of cost or emissions, in installing LNG generation on site, hence favouring a purely cold ironing configuration.

Table 6 illustrates this situation for a configuration where the LNG system has a per-unit cost two-thirds that of the cold ironing system. The search algorithm in this situation has identified LNG generation for the lower power demand connections while favouring cold ironing for the higher demand berths. This gives the best trade-off between system cost and the produced emissions. On the other hand solutions towards each end of the Pareto fronts are more exclusively comprised of single systems; either wholly cold ironing or wholly LNG-based systems.

Finally, Table 7 compares resultant emissions considering the sole cold ironing implementation (centralised topology), with an LNG-only case, as well as the hybrid configuration as described in Table 5 with the current onboard generation. For this particular scenario (port layout of Figure 3, power demands of Figure 11 and considering Spain's generation mix, i.e. 37% gas, 18% nuclear, 6% oil, 13% coal and 24% from renewable sources), the centralised cold ironing topology was identified by the optimisation algorithm as the most suited configuration when considering cold ironing only. It must be pointed out however, that Sulphur emissions in this case are actually increased when compared to low Sulphur (0.1%) Marine Gasoil (MGO) as required to be used onboard by vessels in EU ports.³

Table 7. Comparison of solutions in terms of produced emissions.

Configuration	Energy generated (kWh)	difference (%)	CO ₂ emissions (kg)	difference (%)	SO ₂ emissions (kg)	difference (%)	NO _x emissions (kg)	difference (%)
Onboard generation (using 0.1% Sulphur MGO)	53,144	-	36,669	-	23	-	739	-
Cold ironing	69,028	+29	20,950	-42	27	+17	33	-96
LNG generation	53,144	-	27,741	-24	≈0	-100	112	-84
Combined cold ironing/LNG (configuration from Table 5)	55,646	-	23,964	-34	10	-83	75	-90

Conclusions

Cold ironing (or onshore power supply) presents an alternative to the running of diesel-fuelled generator sets while berthed in port by providing the demanded electrical power to berthed ships from the shore supply network. This is not a zero-emissions option, but rather provides a localised emission-free solution in zones where industrial and residential areas are typically in close proximity. The net resultant airborne emissions are highly dependent on the actual generation mix employed on shore and will clearly be significantly improved in the presence of considerable renewable sources. Conversely in case of a coal-dominated generation mix, CO₂ emissions can actually be increased.^{7, 14}

However cold ironing places a significant power demand on the shoreside grid, which the port might not be able to supply due to infrastructural limitations. The provision of shoreside generation using a clean alternative fuel is a potential solution to this issue with cold ironing. In this work shoreside generation using LNG-fuelled engines is considered as complementing a cold ironing supply.

This paper has presented an approach adopted for the quantitative comparison of various shore supply electrical topologies by modelling different shore network configurations and using power profiles from a RoRo port in North-West Spain. A search algorithm was used to identify the optimal configurations (consisting of hybrid cold ironing and LNG generation) in terms of system cost and emissions produced.

The results show how a significant decrease in airborne emissions is possible compared to current conventional onboard generation approaches. The actual reductions are different for the various emissions; for the particular scenario considered, CO₂ emission savings of around 42% are estimated based on the use of cold ironing as the only shore supply, where a centralised cold ironing topology (with a centrally located frequency converter) was identified as the most appropriate solution. With the option of shoreside generation using LNG as a fuel, lower CO₂ emission reductions are realised while SO₂ emissions were practically reduced to zero. This alternative gives the possibility of a more cost-effective option particularly with a hybridised system which combines elements of cold ironing and shoreside LNG generation.

Significant capital expenditure is required for the implementation of shoreside power supplies, shipside as well as on shore, and the actual cost effectiveness of any such system requires an in-depth operational study considering the size, frequency and duration of ships visiting a particular port. By looking at the trade-offs between the component cost and count and resultant emissions, optimal compromise solutions can be identified, facilitated by the use of a multi-objective nonlinear search algorithm. This gives the most cost-effective system for a particular scenario, taking into account the local generation mix, power profiles and component costs. With shore power supply, emissions in ports can be reduced, if not eliminated, giving localised as well as wide-reaching environmental benefits.

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Appendix

This appendix describes the modelling of additional load losses in a transformer due to non-sinusoidal currents flowing through it. The classification of losses within a transformer can be summarised in Figure 14,¹² highlighting the loss classifications which are affected by the presence of harmonic currents.

Figure 14. Losses in an electrical transformer. Dotted outlines indicate the losses influenced by harmonic currents.

The quantification of the additional losses due to harmonics is based on IEEE Std. C57.110-2008 and the procedure identified therein, by applying the “transformer capability equivalent calculation using data

available from certified test report”.¹² This provides an estimate of the additional losses due to harmonics using limited available data on transformers.

The harmonic spectrum of the drawn current is used to calculate two harmonic loading factors for the additional eddy-current F_{HLeC} and stray losses F_{HLStr} . These are described in equations (3) and (4), which define multipliers to the rated eddy current and stray losses based on the current’s harmonic spectrum.

$$F_{HLeC} = \frac{\sum_{h=1}^{h_{max}} \left(\frac{I_h}{I_1}\right)^2 h^2}{\sum_{h=1}^{h_{max}} \left(\frac{I_h}{I_1}\right)^2} \quad (3)$$

$$F_{HLStr} = \frac{\sum_{h=1}^{h_{max}} \left(\frac{I_h}{I_1}\right)^2 h^{0.8}}{\sum_{h=1}^{h_{max}} \left(\frac{I_h}{I_1}\right)^2} \quad (4)$$

The losses have to be defined for rated conditions first using transformer nameplate data. From Figure 14, the load losses (due to fundamental current flow) at rated voltage and current can be defined as $P_{LLR} = (P_{rat}/\eta_{rat} - P_{rat} - P_{noload})$, where P_{noload} is the core loss, assumed a constant percentage of the transformer’s rated kVA. In turn the total stray losses at rated are given as $P_{TSLR} = P_{LLR} - 3/I_{ph}^2 R_{ph}$ where I_{ph} is the rated phase current. The eddy current losses at rated are defined as being 33% of P_{TSLR} for oil-immersed transformers and 67% in dry-type transformers. The remainder is made up of other stray losses P_{OSLR} .¹²

The rated losses are then scaled proportionally according to the RMS current through the transformer to represent the fundamental stray losses at that loading. The additional harmonic losses are then estimated by multiplying this figure by the harmonic loss factor calculated according to the current’s harmonic spectrum.