A SYSTEMATIC EVALUATION OF ALTERNATIVE OPTIONS FOR THE REDUCTION OF VESSEL EMISSIONS IN PORTS

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ABSTRACT
Transport operations are significant contributors to pollutant emissions across the globe. Maritime transport is responsible for approximately 3% of the global carbon emissions, while emissions around ports from vessel traffic and stationary ships also affect the local environment. This paper presents a framework for examining these impacts considering the environmental footprint of i) ships approaching/departing and ii) berthing at ports, where their emissions impact directly on local air quality and on the exposure of the local population. Speed reduction of ships in transit and cold ironing for berthing ships are examined as possible mitigation techniques to illustrate their potential to reduce emissions for a range of different port and vessel types. Their scope is assessed per call per ship for the reduction of emissions for CO\textsubscript{2}, SO\textsubscript{2} and NO\textsubscript{x}. Both methods are found to be effective, although the results are strongly dependent on the vessel specification and port operating characteristics. For speed reduction, key factors include the fuel used, the size of the vessel, its operating speed and the speed reduction policy adopted. For cold ironing, the port turnaround time, the source of shore electrical power and policies regarding fuel sulphur content are significant. While the two techniques can be applied independently, one of the two may be preferable in a specific port or for specific vessels. Reductions of 55.1 tonnes of CO\textsubscript{2}, 267 kg of SO\textsubscript{2} and 2046 kg of NO\textsubscript{x} are seen for the combination of speed reduction for a large ship and prolonged berth duration using a representative shore electrical supply. These results suggest that policies and practices available to shippers can deliver environmental benefits; however, a clear appraisal for costs and benefits of alternatives is essential to inform effective policy development.

INTRODUCTION
Given the relatively steady rate of growth in maritime logistics, it is necessary that ports consider carefully future energy demand and thus plan ahead for ways to cut their emissions and save energy. Improvement in environmental performance may play a decisive role in each port’s future and upgrade its position in the market, as there are indications that a green port could be a more preferable choice for shippers. Moreover, European Union (EU) legislative Directives and the International Maritime Organization (IMO) mandate environmental standards to which shippers must comply.

The impacts of port operations on the surrounding area can be attributed to three main categories; maritime operations, in-port operations and generated traffic outside the port’s gates. The mechanisms through which each contributes to the port’s environmental footprint differ in each case, as do the potential mitigation measures. This study focuses on the first of these categories; the maritime operations near and in the port. In order to estimate pollutant emissions from vessels it is necessary to differentiate between ships that travel into or out of the port area and stationary ships as in most cases the latter are using their auxiliary engines (with different fuels to the main engines), or connected to shore power (‘cold ironing’). A thorough analysis requires data on the arrival and departure patterns of vessels visiting a port and also the length of time each spends at berth. Finally, for the examination of pollutants in the case the vessel cold irons it is necessary to know the mixture of electrical energy sources that provide power to the vessel.

Emissions generated by vessels that are arriving, berthing and leaving the port are the first contributor in the environmental footprint of a port. The type and size of a ship are important parameters affecting the amounts of emissions it generates. More recently built vessels, using modern technology tend to have a smaller environmental impact as they are obliged to comply with
new IMO regulations (IMO, 2008) and were designed to have improved fuel efficiency (primarily for economic reasons but this also affects the amounts of emissions). Fuel type and operating duty cycle are also key parameters that govern emissions and substantial investigations have been undertaken to model specific nautical engines during operation, linking their emissions with engine load (Trozzi and Vaccaro, 1998).

While there have been studies on the emissions for an entire trip, a different approach is to focus on the immediate area around the port and the potential for port operating policies to influence emissions. Examination at this level also assists in identifying the local environmental impact of the port, for example on air quality and resident exposure to pollution.

**SLOW STEAMING**

Slow steaming refers to the reduction of cruising speeds and is practised due to increased fuel prices, using available excess transport capacity (Benford, 1981). Vessels used to travel on full throttle but have started reducing their speed by around 10% to save fuel and reduce costs by deploying more vessels to accommodate the same transportation demand, (Psaraftis and Kontovas, 2010; Corbett, 2009). While the main driver behind the introduction of slow steaming was economic due to increasing fuel prices, indirectly there are environmental benefits. For example, Carriou (2010) shows that slow steaming reduces emissions by around 11% despite the additional trips required to meet demand.

Slow steaming has also been applied to areas around ports (for example the Port of Los Angeles – POLA) for the last miles of a vessel’s journey (in the “buffer area”) with the objective of improving local air quality (POLA, 2009). The associated cost reductions from reduced fuel consumption are a more minor consideration as these represent only a small fragment of the total trip. In addition, there are indirect benefits that could arise associated with speed reduction around the port. The application of such a scheme would mean that in a buffer area around the port, vessels would be arriving at either a universal speed, or at the very least at reduced speeds. This could improve potential queuing phenomena and help relieve bottlenecks at the berths.

**COLD IRONING**

Cold ironing or Alternative Maritime Power (AMP) or otherwise known as Onshore Power Supply (OPS) refers to the provision of electrical power to a ship at berth using power from a generator or the grid while the ship’s main and auxiliary engines are switched off (European Commission, 2005). The benefits are predominantly local, as the ships are no longer releasing pollutants since the energy demand of the ‘hotelling’ activities of the ship are met by the grid (or other source of power) that feeds the port. As a result, with the use of cold ironing there are no ship emissions (at berth), although there may still be emissions at the energy generation site (since the electrical power supplier may still emit pollutants). To identify the induced emissions from berthing ships that cold iron, one needs to know the energy mixture the port relies on. Power provision in ports varies on a regional or international level. While some ports may have (or plan to build) their own plants for their energy needs, most are still relying on power provision from the regional or national electric power industry. It is apparent that the estimation of induced emissions of pollutants from a port’s operation relies on the identification of the origin of this power (location and type).

The suggested measures could theoretically be applied to any type of vessel regardless of its purpose, and in practice are already used in several ports. Indeed, cold ironing will be mandatory for 50% of vessels visiting Californian ports from 2014, reaching 80% in 2020 (ARB, 2007). This paper considers vessels where both in transit and at berth emissions can be anticipated to be significant. In particular, for reasons of data availability, the focus is on container vessels and calls at large container terminals. However, this analysis framework may be transferred to other cases (such as Ferries, Bulk carriers and RoRo cargo vessels) as data becomes available.
METHODOLOGY

In this paper the focus is on emissions of CO$_2$, SO$_2$ and NO$_x$. Carbon and sulphur emissions depend on the amount of fuel burned, while NO$_x$ is also affected by the engine operating speed. It is assumed that during arrival and departure time, only the main engines are operating, and while at berth only the auxiliary engines are used (IMO, 2008).

The fuel consumption $ME_{buf}$ (tons of fuel) of the main engine in the buffer area is given by;

$$ ME_{buf} = 10^{-6} \times SFOC \times EL \times EP_{main} \times t_{buf} $$

where

- $SFOC$ (g/kWh) is the specific fuel oil consumption
- $EL$ is the Engine Load (%)
- $EP_{main}$ (kW) is the nominal main Engine Power installed in the vessel
- $t_{buf}$ (hours) is the time required to travel the buffer area.

To calculate the carbon emissions one has to multiply $ME_{buf}$ with a factor of 3.17. This factor is found by multiplying the carbon fraction of the fuel used (86.4% as used by Corbett et al.) with a factor of 44/12 to convert the carbon into CO$_2$ (Corbett et al., 2009). For SO$_2$ according to the US EPA the formula used is;

$$ E(\text{sulphur}) \left( \frac{g}{\text{kW} \cdot \text{hr}} \right) = \alpha \times FSFl + b $$

where $\alpha$, $b$ are unitless coefficients. Here $\alpha=2.3735$, and $b$ is statistically insignificant (Dolphin and Melcer, 2009). $FSFl$ is the ‘Fuel Sulphur Flow’ ($\frac{g}{\text{kW} \cdot \text{hr}}$) and is found by;

$$ FSFl = \%S \times \text{Fuel Consumption} $$

where $\%S$ is the percentage of sulphur content in the fuel.

NO$_x$ emissions depend on the engine type and the operating speed. The empirical use of an emission factor ($Nfac$) that ranges according to engine type (Kontovas and Psaraftis, 2009) from 0.087 for slow speed engines to 0.057 for medium speed engines (EMEP/CORINAIR 2002) allows estimation of NO$_x$ emissions.

The above are summarized in the next set of equations:

$$ CO_2 = 3.17 \times SFOC \times EL \times EP_{main} \times t_{buf} $$

$$ SO_2 = 2.3735 \times \%S \times SFOC \times EL \times EP_{main} \times t_{buf} $$

$$ NO_x = Nfac \times SFOC \times EL \times EP_{main} \times t_{buf} $$

These equations allow the estimation of emissions in grams of pollutant. With regards to speed reduction efficiency, the accepted simplification that an increase in speed is proportional to a cubic increase in the load of the engine is used.

$$ \frac{V_1}{V_2} = \left( \frac{EL_1}{EL_2} \right)^3 $$

According to Carriou (2010), SFOC remains approximately unchanged for lowering speed by up to 10% but for reductions of 30% the SFOC increases (as the engine is no longer working at
its optimal operational speed). Nevertheless, slow steaming more than compensates for the increased specific oil consumption as the engine load drops significantly and thus overall $M_{E_{buf}}$ is reduced.

To calculate the emissions of berthing ships the necessary elements are the time spent at berth, the engine type used (auxiliary or in rare cases main), fuel used and engine’s load. The time each vessel spends at berth varies depending on the number of containers that have to be loaded/unloaded, the number of cranes assigned to the vessel and other unique characteristics of the port and ship. The engine’s load while at berth depends on the hoteling activities of the ship, and methodologies used include empirical formulas (Kontovas and Psaraftis, 2009). In this study it is assumed that the auxiliary engine load factor $(E_{L_{aux}})$ is 0.23, as the intention of this work is to present the scope and an indication of potential for reducing emissions in a theoretical study rather than to provide quantitative results for a specific case study. Cold ironing emissions (at source) depend on the energy mixture of the country (or city) producing this power. Appropriate emission factors have then to be selected to convert the energy to pollutant emissions. For some of the countries these factors were publicly available. For those where no data were found, the factors were estimated using a simplified analysis based on the mixture and the average emission factor per type of energy used. It should be noted that while emission factors for the average level may be used, these are not to be confused with marginal emission factors which vary over time depending on current grid loading. The actual emissions generated by a berthing vessel will therefore depend on a number of factors beyond the scope of this investigation. Average emission factors are taken to provide an indicative value.

To identify the energy requirement for AMP, the ship energy demand from the shore needs to be found by dividing the energy required for hoteling by the electric supply efficiency. This study uses a typical value of supply efficiency of 98% as in Alkaner and Zhou (2006). It is assumed that this energy is to be provided by the grid. In order to estimate emissions based on that energy provided by the grid emission factors will be used. For illustration of ‘typical’ and ‘low emission’ cases, the ports of Felixstowe and Santos are considered.

The emissions if the vessel relies on its auxiliary engines are found using a similar methodology as before through the next set of equations.

\[
\begin{align*}
CO_2 &= 3.17 \times SFOC \times E_{L_{aux}} \times E_{P_{aux}} \times t_{berth} \\
SO_2 &= 2.3735 \times 1\% \times SFOC \times E_{L_{aux}} \times E_{P_{aux}} \times t_{berth} \\
NO_x &= N_{fac} \times SFOC \times E_{L_{aux}} \times E_{P_{aux}} \times t_{berth}
\end{align*}
\]

where $E_{P_{aux}}$ is the nominal power of auxiliary engines installed for each ship.

It should be noted that there are examples where AMP was provided from local surplus units. It is apparent that in such case the emissions savings would vary significantly. More specifically, if Renewable Energy sources (RES), nuclear or hydroelectric power is used there would be no emissions in the energy production facilities. There should be an allowance of time to connect and disconnect with the power source. For the Port of Gothenburg the time needed to complete the process is less than 10 minutes (Khersonsky et al. 2007). Cold ironing is not intended for very short berthing durations as the vessel then would continue using its main engines. Cold start emissions are the excess emissions that occur when the engine starts below its normal operating temperature. If the berthing period is very small, cold ironing would not be as efficient as a significant portion of berthing time would be lost to plug and unplug the vessel and due to cold start emissions the environmental benefits would not be that significant.
VESSELS EXAMINED

The study discussed in this paper examined 20 container ships with various combinations of size and engine specifications. These were selected to represent a cross-section of the range of mainstream vessel sizes used for the transportation of containers. The required data of each vessel for the subsequent analysis are: the nominal main engine power installed, the nominal auxiliary power (for ‘hoteling’ activities), average cruising speeds, capacity in TEUs and deadweight tonnage.

The data for these specifications were retrieved from the internet and are shown in Table 1. For vessels where no information was found for the Main Engine Power installed, the following formula was used:

\[
E_{P_{\text{main}}} (\text{kW}) = 0.74 \times (2.581 + 0.719 \times D_{\text{tw}})
\]  

(11)

For the vast majority of the 20 vessels, no information was retrieved about Auxiliary Engine Power installed. Instead, the ratio of power 0.22 (auxiliary engine power to main engine power) as used by Dolphin and Melcer (2008) was applied.

PORTS EXAMINED

The two policies considered here to address in-transit and at-berth emissions could be applied in the majority of ports. However, as each port is unique there are different constraints and levels of performance for each technique when applied to different ports. There are also different regulations ports have to comply with depending on the country or area they are based in. For instance, the Port of Felixstowe lies on the eastern shoreline of the UK, and is within the North Sea’s SO₂ Emission Control Area (SECA) as defined by Regulation 14 (Annex VI of the MARPOL convention, 2008) and thus ships are obligated to burn fuel with no more than 1% of sulphur content until 1st July 2015, reducing to 0.1% sulphur thereafter (DIRECTIVE 2005/33/EC). Moreover, the role of a port also differs from import-export to transshipment with implications to the number of vessel calls and their duration. For example, on average around 250 to 270 vessel calls (container ships, RoRo, and bulk) are made monthly in Port of Felixstowe whereas the respective number of calls in Singapore is close to 11,600 and disproportionate to the throughput handled (Table 2).
The key parameters for the speed reduction scheme is the radius of the zone in which vessels will be asked to slow down and the degree of speed reduction. Many ports are destinations/origins to short distance trips between neighbouring locations. Consequently, a large speed reduction zone would affect a substantial proportion of the total distance of these trips and as such it would seem likely that smaller speed reduction zones would be considered. The benefits of cold ironing are more directly linked to the location of the port, as they depend on the origin of the energy that supplies the vessel. Some ports that have been practising cold ironing are claiming that the origin is from nearby RES (Port of Gothenburg) and as such even globally the mitigation of emissions is close to 100%. In this paper, the global effects are calculated based on the energy mixture of the country of each port. As a result, the energy policy of the country as a whole as well as the potential for RES or nuclear will govern the amount of emissions saved through cold ironing now and most importantly in the future since the energy mix of a country is expected to change over the years. Oil price may also be a key parameter to the expansion of cold ironing in ports. Increased oil prices could offer ship-owners an additional motivation to migrate towards the use of shorepower (if this is provided at competitive prices), while at berth, to avoid using expensive fuel. Through the Directive 2009/28 EC, EU Member States are obliged to increase the participation of clean energy sources to their energy mixture and cold ironing can be expected to have increasing environmental benefits on a global level. In Table 2, key characteristics of the ports used and the energy mixture of the country (state for USA) are presented as taken from port and relevant ministries websites.

<table>
<thead>
<tr>
<th>Port</th>
<th>Container throughput 2011 (million TEUs)</th>
<th>Country</th>
<th>Coal</th>
<th>Fuel and Liquid Gas</th>
<th>Nuclear</th>
<th>RES (including Hydro)</th>
<th>Others (including imports)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Singapore</td>
<td>29.9</td>
<td>Singapore</td>
<td>0</td>
<td>97.4</td>
<td>0</td>
<td>0</td>
<td>2.6</td>
</tr>
<tr>
<td>Rotterdam</td>
<td>11.9</td>
<td>The Netherlands (2004)</td>
<td>11.2</td>
<td>82.9</td>
<td>1.2</td>
<td>2.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>7.9</td>
<td>USA (California)</td>
<td>9</td>
<td>37</td>
<td>19</td>
<td>22</td>
<td>13</td>
</tr>
<tr>
<td>Felixstowe</td>
<td>3.3</td>
<td>UK</td>
<td>28.9</td>
<td>44.2</td>
<td>17.3</td>
<td>7.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Melbourne</td>
<td>2.5</td>
<td>Australia2010</td>
<td>37.5</td>
<td>57.7</td>
<td>0</td>
<td>4.8</td>
<td>0</td>
</tr>
<tr>
<td>Santos</td>
<td>2.7</td>
<td>Brazil</td>
<td>1.4</td>
<td>15</td>
<td>2</td>
<td>75.9</td>
<td>5.7</td>
</tr>
<tr>
<td>Piraeus</td>
<td>1.6</td>
<td>Greece2009</td>
<td>48.9</td>
<td>26.3</td>
<td>0</td>
<td>17</td>
<td>7.9</td>
</tr>
</tbody>
</table>

**SELECTION OF BUFFER ZONE**

The first step for the estimation of emission reductions from slow steaming is to define an area within which ships would be asked to travel at a lower speed. POLA operates this scheme for two zones at 20 nautical miles (NM) and at 40 NM offering a differential financial incentive to complying ships. The selection of the radius is depending on the port’s individual characteristics and policy. A reasonable policy which could be applied universally from all ports considering such a scheme would be to operate differential zones and reward each vessel according to the distance over which they operate slow steaming. This may allow, for example, longer distance trips to economically adopt this method over longer distances. For example, selecting 20 or 40 NM for the Port of Felixstowe would seem rather unrealistic for trips that in total have lengths of only 200 to 400 NM. While there are some regular direct services to distant ports (for instance Piraeus, Newark and Singapore) where a larger buffer zone would not increase significantly the total travel time (proportionally), the vast majority are shorter trips. Here it is assumed that each vessel will reduce its speed within an area defined by the port only. It is also assumed that during the last/first 0.5 NM, when the vessel is maneuvering to berth/depart, the procedure will not be different to baseline scenarios, and as such the speed and engine load will be unaffected by slow steaming in the previous section of the trip. On certain occasions a small difference may be observable due to
different engine temperatures but for the purposes of this study such concerns are neglected due to
the small distances involved.

The speed reduction policy at POLA is granting monetary benefits to all vessels reducing their
speed to 12 knots. This means that different vessels with varying normal operating speeds would
have significant differences in emissions saved. Another way to present speed reduction would be
to reduce the speed of every vessel by a percentage. This would allow all ships to have the option of
participating and reducing their emissions, including ships that normally travel at lower speeds than
the proposed maximum speed limit. In the subsequent section, emission savings per ship per call are
presented, assuming a universal reduction to 12 knots.

RESULTS

The following table summarizes the emissions saved from the speed reduction to 12 knots for each
of the examined ships. The sulphur content was taken at 1% for the results of this analysis and the
zone selected to cover 12 NM.

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Average speed (knots)</th>
<th>%ΔV</th>
<th>%ΔSFOC</th>
<th>%Δbuf</th>
<th>δCO₂ (kgs)</th>
<th>δSO₂ (kgs)</th>
<th>δNOₓ (kgs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.4</td>
<td>3.2</td>
<td>0</td>
<td>3.33</td>
<td>-325</td>
<td>-2.43</td>
<td>-5.85</td>
</tr>
<tr>
<td>2</td>
<td>13</td>
<td>7.7</td>
<td>0</td>
<td>8.33</td>
<td>-1,037</td>
<td>-7.77</td>
<td>-18.65</td>
</tr>
<tr>
<td>3</td>
<td>14</td>
<td>14.3</td>
<td>0.00</td>
<td>16.67</td>
<td>-1,941</td>
<td>-14.53</td>
<td>-34.89</td>
</tr>
<tr>
<td>4</td>
<td>19</td>
<td>36.8</td>
<td>0.1</td>
<td>58.33</td>
<td>-3,980</td>
<td>-29.80</td>
<td>-71.56</td>
</tr>
<tr>
<td>5</td>
<td>18</td>
<td>33.3</td>
<td>0.1</td>
<td>50.00</td>
<td>-3,826</td>
<td>-28.65</td>
<td>-68.79</td>
</tr>
<tr>
<td>6</td>
<td>9.9</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>14.9</td>
<td>19.5</td>
<td>0.05</td>
<td>24.17</td>
<td>-13,227</td>
<td>-99.04</td>
<td>-237.83</td>
</tr>
<tr>
<td>8</td>
<td>16</td>
<td>25.0</td>
<td>0.05</td>
<td>33.33</td>
<td>-16,175</td>
<td>-121.11</td>
<td>-290.84</td>
</tr>
<tr>
<td>9</td>
<td>16</td>
<td>25.0</td>
<td>0.05</td>
<td>33.33</td>
<td>-16,405</td>
<td>-122.83</td>
<td>-294.97</td>
</tr>
<tr>
<td>10</td>
<td>15.3</td>
<td>21.6</td>
<td>0.05</td>
<td>27.50</td>
<td>-25,518</td>
<td>-191.06</td>
<td>-458.84</td>
</tr>
<tr>
<td>11</td>
<td>13</td>
<td>7.7</td>
<td>0</td>
<td>8.33</td>
<td>-12,025</td>
<td>-90.03</td>
<td>-216.22</td>
</tr>
<tr>
<td>12</td>
<td>20</td>
<td>40.0</td>
<td>0.1</td>
<td>66.67</td>
<td>-33,252</td>
<td>-248.97</td>
<td>-597.91</td>
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<tr>
<td>13</td>
<td>17</td>
<td>29.4</td>
<td>0.10</td>
<td>41.67</td>
<td>-27,786</td>
<td>-208.04</td>
<td>-499.62</td>
</tr>
<tr>
<td>14</td>
<td>17</td>
<td>29.4</td>
<td>0.1</td>
<td>41.67</td>
<td>-29,267</td>
<td>-219.14</td>
<td>-803.24</td>
</tr>
<tr>
<td>15</td>
<td>13.1</td>
<td>8.4</td>
<td>0</td>
<td>9.17</td>
<td>-14,231</td>
<td>-106.55</td>
<td>-390.57</td>
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<tr>
<td>16</td>
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<td>-872.35</td>
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<tr>
<td>17</td>
<td>15.7</td>
<td>23.6</td>
<td>0.05</td>
<td>30.83</td>
<td>-29,528</td>
<td>-221.08</td>
<td>-810.38</td>
</tr>
<tr>
<td>18</td>
<td>20</td>
<td>40.0</td>
<td>0.10</td>
<td>66.67</td>
<td>-38,596</td>
<td>-288.98</td>
<td>-1,059.26</td>
</tr>
<tr>
<td>19</td>
<td>17.2</td>
<td>30.2</td>
<td>0.05</td>
<td>43.33</td>
<td>-31,871</td>
<td>-238.63</td>
<td>-874.68</td>
</tr>
<tr>
<td>20</td>
<td>8.6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Graph 1 illustrates the reduction in CO₂ emissions per call for different buffer zones for the 20
vessels against their TEU capacity. As these emissions only depend on the area where speed
reduction is performed, it is certain that interesting price discrimination schemes should be
researched according to a port’s position and links to other ports. There are two ships which have
zero emissions saved as their average cruising speed is less than the 12 knot speed limit examined
here. For these ships an interesting approach would be to examine a percentage speed reduction.
In Table 4 the estimated emissions from the hoteling activities of the 20 vessels are shown. If each vessel relied on cold ironing, locally the emissions would be close to zero. Globally, the emissions due to electrical energy consumption is shown for the UK energy mixture and for duration of berths as published on the website of Port of Felixstowe (http://www.portoffelixstowe.co.uk). In terms of magnitude, CO$_2$ and NO$_x$ emissions would benefit significantly from cold ironing. Regarding SO$_2$ emissions, a small detrimental effect is observed due to the relatively high SO$_2$ emission rate for the UK grid, and the fact that the Port of Felixstowe operates in a SECA zone with low sulphur fuel. A sensitivity analysis on the turnaround time of vessels will help improve the understanding of cold ironing potential for emissions savings per container handled or per vessel call.

### Table 4: Emissions of AE during berth

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Berthing time(hours)</th>
<th>$EP_{max}$ (kW)</th>
<th>Emissions from Auxiliary engines(kg/call)</th>
<th>Emissions from grid generation(kg/call)</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
<td>$CO_2$</td>
<td>$SO_2$</td>
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Graph 2 presents the carbon emissions saved per call for each of the 20 ships examined. More specifically, the carbon emissions that would be generated by the auxiliary engines are shown against the global emissions from cold ironing assuming the port is either Felixstowe or Santos (to represent a very low emission electrical grid mix). The auxiliary engine emissions are essentially the local benefits that would be enjoyed if the vessel relied on cold ironing.

It can be observed that for a port relying on cleaner energy sources, the scope for global reduction is significantly higher. As seen in Graph 2, if the Port of Santos was to provide AMP, for most of these calls the global savings would be much higher than for instance for the Port of Felixstowe. These calculations were made using emission factors published for UK and Brazil. A similar analysis could have been performed for SO$_2$ and NO$_x$ oxides, but was not feasible due to lack of appropriate emission factors for Santos. Even though Brazil relies on RES for a very big percentage of its energy use, some RES do emit SO$_2$ and NO$_x$ emissions (for instance biomass) which cannot be neglected. It is expected that in countries which do not heavily rely on coal, SO$_2$ emissions would be reduced through ships using cold ironing. The sulphur content of the fuel used by the auxiliary engines is important. The results of Table 4 suggest that SO$_2$ emissions are actually
higher using shore power. This is reasonable as these numbers are for auxiliary engines using very low sulphur content (Felixstowe belongs in a SECA zone). Nevertheless, local improvements are more important in the case of sulphur and nitrogen pollutants due to their damaging effects to health of exposed population.

Graph 3 illustrates the carbon emissions per hour for the 20 vessels that were examined in this study in scenarios that involve the use of their auxiliary engines (baseline scenario) or cold ironing either at Felixstowe or at Santos. Again the local savings would be equal to the emissions generated at the baseline scenario, but interesting conclusions can be drawn for the global savings as well.

![Graph 3: CO₂ Emissions per hour at berth per ship](image)

It is apparent that cold ironing is more beneficial for larger vessels that also tend to spend longer periods of time at berth (according to the dataset used). In Graph 3 it appears that the relation of TEU capacity and per hour emissions is almost linear. It would be very interesting to proceed with an analysis on a larger dataset with vessels of similar sizes but different age to obtain a better understanding of the potential of cold ironing over the coming years and with different engine load factors (and thus energy requirements) according to real world data from monitoring of the vessels during their hoteling activities. Despite the fact that cold ironing can be expected to have more potential as the years go by due to improvements in the sources of grid energy, advances in marine engine technologies are expected to slightly counter this through optimized performance.

In conclusion, speed reduction appears to have greater scope for emission reduction in absolute terms, but it must be acknowledged that in this analysis a relatively low engine load factor has been selected for the auxiliary engines used during hoteling activities. It would be reasonable to perform a stochastic analysis around the value of the load factors. Regarding the future of the two techniques, cold ironing will most likely have its potential increased (on the global level) since there are efforts for the energy mixtures to become 'greener'. The benefits of speed reduction will also change according to advances in marine engine technologies and perhaps regulations on fuel sulphur content. Speed reduction at the moment seems as an easy to use policy with no significant
capital investments required compared to cold ironing which requires investments and depends on retrofitting ships and will probably require a considerable amount of time to return the initial investments. Both policies may help the public image of ports with the potential for cost savings if ports are included in emissions charging or other penalty schemes.

3. CONCLUSION AND FUTURE SUGGESTIONS

This paper presents a methodology to estimate the environmental benefits of methods to reduce emissions from in-transit and at-berth ships. Cold ironing and slow steaming near the port areas are considered as example interventions. This method could be extended to represent alternative port policies for various port types. A number of vessels were examined according to real operational data and the results for the scope of reduction in pollutants was shown. It appears that the reduction in emissions from reducing speeds is more significant than those provided by cold ironing for the vessels examined. However, this may not always be the case as cold ironing performance is governed by the time spent at berth, the engine load and the local electrical energy supply mix which may vary significantly in different ports. In order to have a better understanding of the scope for reduction a sensitivity analysis with regards these parameters is suggested.

Both techniques could be used at the same time as long as the vessels could be plugged for AMP and the ports equipped with the technology. It appears that speed reduction offers more savings in absolute terms, but cold ironing could be more efficient if higher load factors were required or for longer periods of berth. Another major difference is that cold ironing as presented here offers a local air quality advantage by eliminating at-berth emissions in the port (although there may be emissions at the power plant), whereas speed reduction only limits the pollutants. The scope of cold ironing could also be expanded over the next few years as RES are expected to participate more in the energy mixtures of most countries and as port authorities may consider investing in RES in port. Ideally, vessels could choose to practise both these measures which would not only improve local air quality, but also reduce total emissions of these pollutants.

An analysis was carried out using a sample of 20 container vessels representative of various capacity and engine power configurations. Subject to data availability, the framework presented here could be applied to a comparative analysis of ports around the world with different individual characteristics. Consideration of data over an extended period would also enable an evaluation of emissions saved per port instead of per call. The necessary data would be the ‘mixture’ of different vessels calling at each port and most importantly the turnaround time for each vessel. Then this framework will be able to estimate the environmental gains based on the number of vessels complying with either one or both of the policies examined here. Finally, these two options should also be evaluated economically subject to data availability for cost and revenue elements where the additional delays from the slower speeds near port and the connecting/disconnecting time for cold ironing will also have to be presented in monetary terms. It is expected that the characteristics of port sizes, operational profiles and surroundings will affect the extent to which each method may be implemented successfully. Port activities including optimization of arrival and departure routes vessels have to travel, in-port maneuvering and the cargo handling operations of the port can all offer additional areas for potential emissions reduction. The careful evaluation of alternative technologies (e.g. extensive port electrification) is required to investigate their potential costs and benefits.
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