UNIVERSIDAD DE LAS PALMAS DE GRAN CANARIA

Programa de Doctorado en Turismo, Economia y Gestion

ESSAYS ON SUSTAINABILITY AND PERFORMANCE IN PORTS

A thesis submitted for the degree of Doctor of Philosophy

Thomas Spengler

Berlin, 2023

UNIVERSIDAD DE LAS PALMAS
DE GRAN CANARIA

ESCUELA DE DOCTORADO

Programa de Doctorado en Turismo, Economia y Gestion

ESSAYS ON SUSTAINABILITY AND PERFORMANCE IN PORTS

Thesis submitted for the degree of Doctor of Philosophy by Thomas Spengler and supervised by Prof. Beatriz Tovar and Prof. Gordon Wilmsmeier.

Supervisor 1	Supervisor 2	PhD Student
Beatriz Tovar	**Gordon Wilmsmeier**	**Thomas Spengler**

Las Palmas de Gran Canaria, a 08 de Noviembre de 2023

Acknowledgements

I would like to acknowledge and express my gratitude to the support of Universidad de las Palmas de Gran Canaria and City University of Applied Sciences, Bremen. Also, I would like to thank the Economic Commission for Latin America for allowing me to collect data on energy consumption as well as productivity in ports, without which it would not have been possible to derive a major portion of the valuable insights of this thesis.

Furthermore I would like to thank my supervisors Prof. Beatriz Tovar and Prof. Gordon Wilmsmeier for their continuous support and professional excellence.

Finally, I would like to extend the acknowledgements to Ina Budde, who has accompanied me during the time of the completion of this academic degree. Thank you.

Contents

List of Tables

Chapter 1

Chapter 2

Chapter 3

List of Figures

Chapter 2

Chapter 3

Introducción

En los últimos años, el debate académico sobre la eficiencia y la productividad de la logística portuaria se ha ampliado para incluir aspectos que, en términos muy generales, están relacionados con la generación y el consumo de energía y las emisiones resultantes. (He et al., 2017; Martínez-Moya et al., 2019; Spengler y Wilmsmeier 2019; Tichavska y Tovar 2019). El creciente interés por este tema está estrechamente relacionado con el aumento de los costes energéticos, así como con la importancia del debate sobre el desarrollo sostenible, ya que los buques representan el 90% del transporte internacional y el 2,2% de las emisiones mundiales (Smith et al., 2015).

Aunque puede considerarse que la cuestión general de las emisiones de gases de efecto invernadero (GEI) y el calentamiento global es uno de los factores clave que han provocado esta ampliación del interés académico, es necesario tener en cuenta que el consumo de combustibles fósiles y, por tanto, la emisión de gases que se derivan de su combustión, también tienen importantes implicaciones a escala local. Además del dióxido de carbono (CO2), la combustión genera otros gases como los óxidos de nitrógeno (NOx), el dióxido de azufre (SO2) y las partículas (PM). Aunque los efectos de esos contaminantes climáticos de corta duración son insignificantes a escala mundial, tienen un impacto sustancial a escala local, siendo el factor de impacto negativo predominante el que afecta a la salud humana.

Los políticos pretenden abordar este último problema mediante una serie de actividades reguladoras en las zonas urbanas. Por lo que respecta a la logística portuaria, el "cold ironing" se percibe como una medida importante que puede desplegarse para reducir la contaminación atmosférica en las proximidades de los puertos (Cullinane y Cullinane, 2019; Pettit et al., 2018). El cold ironing, a veces denominado también shore-to-ship power (SSP), es una tecnología en la que los buques atracados se suministran de energía eléctrica desde tierra, en lugar de que el propio buque genere electricidad utilizando sus motores auxiliares. Así, la contaminación atmosférica que pudiera derivarse del proceso de producción de energía a través de los motores auxiliares se desplazaría geográficamente a la ubicación de la central eléctrica lo cual sería, ya de por si una ventaja, dado que las centrales eléctricas suelen estar situadas en zonas menos densamente pobladas que los puertos. Además, podrían obtenerse beneficios adicionales, derivados de la eficiencia de escala en la producción de energía, alcanzables cuando el proceso tiene lugar en una central eléctrica en lugar de a través de muchos pequeños motores auxiliares. Se han realizado análisis de programas de subvenciones para el cold ironing como estrategia potencial (Wu y Wang, 2020) y, aunque el cold ironing tiene un coste marginal relativamente alto si se considera como una mera tecnología de reducción del CO2 (Wan et al., 2018), se demuestra que los beneficios del cold ironing son sustanciales si se considera como una forma de reducir el coste externo para la sociedad en general y para las ciudades portuarias en particular.

Esta tesis tiene como objetivo examinar la eficiencia y los aspectos medioambientales de la logística portuaria, centrándose en el consumo de energía y sus implicaciones. Para ello, aborda tres cuestiones de investigación interconectadas. En primer lugar, la tesis investiga si la consideración de variables relacionadas con la energía y la desagregación del producto producirá resultados significativamente diferentes al medir la eficiencia de las terminales de contenedores. Este análisis proporciona la base para comprender la relación entre el consumo de energía y la eficiencia general en las operaciones de las terminales portuarias. Partiendo de esta base, la tesis explora a continuación el potencial del cold ironing como medio para reducir la contaminación atmosférica en los puertos. Al evaluar los beneficios del cold ironing en el contexto del sistema portuario español, la tesis ofrece una perspectiva sobre su papel en la mitigación de las externalidades medioambientales asociadas a la producción de energía a bordo. Por último, la tesis hace una profunda valoración medioambiental de las emisiones del transporte marítimo dentro de los puertos, considerando distintos tipos de buques, en cuatro puertos españoles. Al permitir una comprensión exhaustiva de los costes externos asociados a las emisiones de los buques atracados, proporciona información sobre las áreas en las que la implantación de instalaciones de cold ironing reportaría mayores beneficios. Aunque hubiera sido deseable incluir las emisiones en el primer capítulo (emisiones relacionadas con la parte terrestre del puerto), no fue posible por falta de datos. La tesis concluye con un capítulo final en el que se exponen los resultados más relevantes de la tesis.

El debate sobre el desarrollo sostenible y el aumento de los costes de la energía son responsables de la atención creciente que se viene prestando al consumo de energía y, en consecuencia, a las emisiones en los puertos y, por ende, en las terminales de contenedores.

Las terminales de contenedores se enfrentan entonces a la decisión inicial de la dirección sobre si adquirir equipos alimentados por gasóleo o por electricidad. El capítulo 1, titulado "¿Son clave la desagregación de la producción y las variables energéticas a la hora de medir la eficiencia de las terminales de contenedores?", publicado en "Maritime Policy & Management", aborda la cuestión de si la consideración de variables relacionadas con el consumo energético y la desagregación de la producción arrojarían resultados sustancialmente diferentes al medir la eficiencia de las terminales de contenedores.

Partiendo de una discusión sobre los conceptos teóricos y la selección de variables para medir la dimensión energética de la eficiencia de las terminales, hasta donde saben los autores, ésta es la primera aplicación del Análisis Envolvente de Datos (DEA) que compara resultados con y sin consumo de energía, así como agregando y desagregando los productos (manipulación de contenedores secos y refrigerados). Los resultados revelan cómo la desagregación de la producción da lugar a puntuaciones de eficiencia sustancialmente distintas y constituyen un primer paso para demostrar la relevancia de la desagregación de la producción y la inclusión de las variables de consumo energético en los estudios de eficiencia de las terminales de contenedores.

Por lo que respecta a la desagregación del producto, el argumento de este capítulo es que la generalización, comúnmente aplicada, de medir la producción de las terminales de contenedores utilizando una medida agregada como el número de contenedores o el número de TEUs manipulados podría, en algunas circunstancias, sesgar los resultados de un análisis de eficiencia entre terminales de contenedores. Para ilustrar este problema, en este capítulo se analizan los niveles de eficiencia de terminales de contenedores que manipulan una proporción comparativamente alta/baja de contenedores refrigerados. La hipótesis es que, a pesar de tratarse de cajas con tamaños estándar, los requerimientos de manipulación de ambos tipos de contenedores (refrigerados y no refrigerados o secos) varían significativamente, por lo que deben considerarse productos diferentes a la hora de medir la eficiencia de la terminal, en lugar de agregarlos en una única medida, como es la práctica habitual en la literatura.

El problema se intensifica aún más por consideraciones geográficas, es decir, cuando se realizan análisis que abarcan terminales que se encuentran en diferentes áreas geográficas, ya que las cuotas de contenedores refrigerados pueden diferir significativamente entre las terminales de contenedores consideradas. Efectivamente, esta cuota es en general mayor en regiones como América Latina que, por ejemplo, en Europa por lo que un análisis de eficiencia, por naturaleza comparativo, entre terminales de contenedores ubicadas en ambas regiones que utilizara una medida agregada del producto, podría verse sesgado por la existencia de una cuota sistemáticamente diferente de contenedores refrigerados en las terminales de contenedores de ambas regiones.

Por lo que respecta a las variables que representan consumos energéticos, como destaca la revisión de la literatura realizada, éste es el primer trabajo que incluye el consumo de energía como factor de producción en un análisis DEA de la eficiencia de las terminales de contenedores, y lo hace a través de dos variables: el consumo de electricidad (kwh) y el consumo de gasóleo (litros).

Obtener los datos para llevar a cabo esta investigación no fue una tarea trivial. Se desarrolló una herramienta en línea que permitía a los operadores de las terminales introducir datos sobre los factores productivos utilizados (trabajo, consumo de energía, etc.) y los contenedores manipulados. La colaboración con la Comisión Económica de las Naciones Unidas para América Latina y el Caribe (CEPAL) y las partes interesadas del sector, hizo posible recopilar datos de más de 100 terminales. Sin embargo, al final sólo se utilizaron 26 terminales en esta investigación, debido a diversas lagunas de datos que no pudieron completarse. Se consideró que los datos disponibles eran suficientes para abordar el análisis.

Se calcularon un total de cuatro modelos para poder hacer afirmaciones sólidas sobre la necesidad de diferenciar el producto y considerar la energía como un factor productivo: (1) un modelo en el que no se incluyen los factores productivos electricidad y gasoleo y se desagrega el producto en contenedores secos y refrigerados, (2) un modelo en el que la electricidad y el gasóleo se consideran factores productivos adicionales y no se desagrega el producto, considerandose el total de contenedores, (3) un modelo en el que los contenedores secos y refrigerados se consideran productos separados, pero la electricidad y el gasóleo no se consideran factores productivos y (4) un modelo en el que se desagrega el producto en contenedores secos y refrigerados y además se incluyen la electricidad y el gasóleo como factores productivo adicionales.

Los resultados revelan cómo la desagregación del producto y la inclusión de variables que recogen los consumos energéticos conducen a puntuaciones de eficiencia sustancialmente diferentes. El análisis en profundidad de las terminales de contenedores individuales y sus homólogas revela que este cambio en las puntuaciones de eficiencia no es arbitrario, sino que, en muchos casos, está estrechamente relacionado con la proporción de contenedores refrigerados que se mueven por una terminal determinada.

El resultado del modelo con la energía como factor productivo y los productos diferenciados no era sustancialmente diferente del modelo en el que la energía no se consideraba un factor, pero los productos seguían estando diferenciados. Esto podría deberse a que las dos variables están muy correlacionadas. En conclusión, puede afirmarse que, al menos, es necesario diferenciar los productos cuando se realicen nuevas investigaciones sobre la eficiencia portuaria en las que se vayan a comparar terminales con porcentajes muy diferentes de contenedores refrigerados.

Mientras que el capítulo 1 se mantiene dentro de los límites organizativos del puerto, los capítulos 2 y 3 se centran en los buques del puerto, sus externalidades y su posible reducción mediante la tecnología de cold ironing. Aunque hubiera sido deseable incluir también las emisiones en el capítulo 1 (emisiones de tierra), no fue posible por falta de datos fiables.

El capítulo 2, titulado "Potencial del cold ironing para la reducción de las externalidades de las emisiones del transporte marítimo en puerto: El caso del sistema portuario español de titularidad estatal" y publicado en "Journal of Environmental Management", proporciona información sobre el potencial del cold ironing para la reducción de las externalidades originadas por los buques atracados en los puertos españoles.

Se estimó el coste externo derivado de las emisiones de CO2, NOx, SOx y PM de los buques atracados en el sistema portuario español durante 2016, proporcionando una evidencia empírica a nivel de toda España sobre dónde existen las mayores externalidades y dónde, a nivel de puerto por puerto, la introducción del cold ironing podría producir el mayor potencial de reducción de dichas externalidades. También se obtuvieron parámetros de ecoeficiencia. Se ha comprobado que la población de la ciudad portuaria, así como la composición del tráfico, son factores clave a la hora de determinar los costes externos, y deben tenerse en cuenta cuando se tome la decisión de inversión sobre dónde ubicar el cold ironing.

Hay que tener en cuenta que la introducción del cold ironing requiere una importante inversión de capital. En tierra, hay que desarrollar una infraestructura para suministrar electricidad y convertir la frecuencia de la red eléctrica nacional (normalmente 50 Hz en Europa) a la frecuencia necesaria a bordo de los buques (normalmente 60 Hz). Además, los buques deben someterse a modificaciones sustanciales para poder recibir electricidad de tierra. Estas inversiones son necesarias para garantizar el éxito de la implantación del cold ironing.

Si se ignoran las externalidades asociadas a la producción de energía a bordo, se subestimaría considerablemente el coste global de la producción de energía a bordo de los buques. En consecuencia, también podría subestimarse la viabilidad económica de la tecnología. Por tanto, es crucial tener en cuenta todo el alcance de los costes externos al evaluar los beneficios potenciales del cold ironing. El Capítulo 2 proporciona cifras de costes externos derivados de las emisiones de los buques atracados en los puertos del sistema portuario español, y que pueden considerarse requisitos previos cuando se pretende internalizar los mencionados costes externos. De este modo, se puede tomar una decisión informada que permita priorizar dónde tendría mayor impacto la inversión sustancial en tecnología.

Los cálculos se realizaron siguiendo distintos enfoques metodológicos que se seleccionaron a partir de una revisión exhaustiva de los propios enfoques y de la bibliografía pertinente. Los factores de costes externos para NOx, SO2 y PM se obtuvieron de BeTa, que tiene en cuenta numerosos factores relacionados con la salud, la población de la respectiva ciudad (portuaria) e incluso otros factores como el impacto negativo de los contaminantes climáticos de corta duración en el rendimiento de los cultivos y las estructuras. El factor de coste externo para el CO2 se obtuvo de Delft e Infras (2011), que proporciona una estimación alta y otra baja.

Esta es la primera vez que se realiza en España un análisis de los costes externos y del potencial de ahorro asociado a la utilización del cold ironing que abarca todo el sistema portuario. Resumiendo, los resultados fueron los siguientes: Los costes externos totales incluyendo los efectos locales y globales de las emisiones de los buques atracados oscilaron entre 326 y 440 millones de euros. Barcelona y Valencia presentaban los costes externos más elevados con gran diferencia, seguidas de Bilbao, Algeciras y Las Palmas.

Además, se calcularon los indicadores de ecoeficiencia, "coste externo por barco" y "coste externo por hora", para ofrecer conclusiones más sólidas. A partir de las conclusiones generales y de los indicadores de ecoeficiencia, se hacen tres observaciones principales. En primer lugar, aunque el tamaño de la población influye mucho en la estimación de los costes externos, no es el único factor determinante a la hora de comparar los indicadores de ecoeficiencia. En segundo lugar, la composición del tráfico, incluidos los tipos de buques (por ejemplo, cruceros, graneleros, contenedores), también influye en los costes externos. Por último, para comprender plenamente la sostenibilidad en los puertos, son necesarios análisis más refinados. Estos análisis deberían incorporar indicadores de ecoeficiencia y cifras desglosadas en función del tipo de buque.

Aunque este artículo ofrecía una visión de muchos aspectos diferentes de los costes externos en el sistema portuario español y su posible reducción mediante el cold ironing, aún quedaban cosas por investigar, ya que este artículo ofrecía una visión limitada de la dimensión temporal, así como de los costes externos en función del tipo de buque, que se abordaron en el capítulo siguiente.

El capítulo 3, titulado "Valoración ambiental de las emisiones del transporte marítimo intraportuario por sector de actividad en cuatro puertos españoles" y publicado en el " Marine Pollution Bulletin", presenta las cifras de los costes externos de los buques atracados en cuatro puertos españoles: Las Palmas de Gran Canaria (74,4 millones de euros), Tenerife (20 millones de euros), Palma de Mallorca (19,5 millones de euros) y Pasaia (1,5 millones de euros). Para ello se ha tenido en cuenta la necesidad de datos más granulares reconocida en el capítulo anterior. Por lo tanto, no sólo se facilitan cifras puerto por puerto, sino también cifras por tipo de buque y puerto desde una perspectiva de series temporales.

Los costes externos por subsectores del transporte marítimo permiten comprender mejor las relaciones entre los tipos de buques y los costes externos. El objetivo es asignar correctamente las responsabilidades entre los distintos sectores del transporte marítimo dentro de un puerto y comprender mejor los beneficios potenciales de la aplicación de tecnologías de reducción, como el cold ironing. Se descubrió que los beneficios potenciales del cold ironing diferían enormemente entre los distintos puertos analizados.

Los tipos de buques considerados fueron buques de carga general, portacontenedores, de crucero, de carga refrigerada, de carga rodada (RoRo) y otros. También hay que tener en cuenta el coste de capital relativamente alto que supone la implantación del cold ironing en los puertos y a bordo de los buques. Los tipos de buques mencionados suelen atracar en lugares diferentes. Esto se debe a los diferentes requisitos en términos de infraestructura. Para abordar la cuestión de dónde podría obtenerse el mayor beneficio de la instalación de cold ironing, se constató que los beneficios potenciales del cold ironing difieren enormemente entre los distintos puertos.

La metodología empleada se basa en el enfoque de la vía de impacto (IPA, por sus siglas en inglés), que se ha convertido en una norma para estimar los costes externos asociados a las emisiones atmosféricas. El apartado de resultados y discusión presenta los costes externos locales estimados para cada puerto utilizando distintos modelos y escenarios. Se analizan las variaciones entre los distintos modelos, concretamente NEEDS, CAFÉ y BeTa, y se elige la metodología BeTa para el análisis posterior debido a las diferencias insignificantes en comparación con otros enfoques.

El coste externo de la escala de un barco en un puerto depende de diversos factores. Hemos encontrado diferencias entre tipos de buques que no pueden explicarse sólo por el número de escalas. Algunas están claramente relacionadas con el tiempo medio de atraque, mientras que otras pueden asociarse a las características del buque en cuestión (es decir, tipo de buque, edad, etc.). Los graneleros de líquidos, por ejemplo, suelen tener un tamaño medio mayor que los portacontenedores o los buques de carga rodada. Pero el tamaño del buque tampoco puede explicar por sí solo las diferencias. Los buques de carga refrigerada suelen ser pequeños; sin embargo, necesitan producir una cantidad relativamente alta de electricidad a bordo del buque para mantener la temperatura en la bodega de carga, incluso en el atraque.

La gran diferencia en los patrones de costes externos de los distintos tipos de buques hace necesario examinar la cuestión desde una perspectiva de indicadores relativos en lugar de valores absolutos. Además, los indicadores de ecoeficiencia "coste externo por hora de amarre" y "coste externo por escala" se calculan por tipo de barco, lo que es necesario para comprender mejor los distintos costes externos asociados a los diferentes tipos de buques. Se comprobó que los indicadores de ecoeficiencia difieren sustancialmente entre tipos de buques y puertos. Las razones de esos costes externos variables pueden atribuirse con toda seguridad a una serie de factores, como la edad media y el tamaño de determinados tipos de buques, pero también a factores más bien intrínsecos asociados a los propios tipos de buques, como la duración de las operaciones de carga o el consumo de energía durante el atraque.

Este capítulo ha destacado la gran importancia que tienen los efectos locales de las emisiones, en términos de costes externos, sobre las ciudades y regiones situadas en las inmediaciones directas de un puerto. Aunque se ha demostrado que los costes externos de un puerto están relacionados con el tipo de buque en cuestión, las conclusiones dejan margen de interpretación porque también puede haber grandes diferencias dentro de un mismo tipo de buque. Además, las conclusiones de este capítulo subrayan el gran potencial de las tecnologías de reducción, como el cold ironing. Ahora es posible evaluar hasta qué punto esas tecnologías de reducción tienen sentido y apuntan hacia la necesidad de evaluar el potencial en cada puerto individual por tipo de buque, ya que las diferencias son evidentes.

En resumen, como se ha demostrado en esta tesis, los puertos han empezado a explorar formas de integrar la gestión medioambiental en la economía y la sociedad locales. Entre ellas se incluye la medición del rendimiento (ecoeficiencia) mediante la evaluación medioambiental (por ejemplo, las emisiones) en relación con los factores económicos (producción) y el apoyo al diseño de instrumentos de política que tengan en cuenta los indicadores de ecoeficiencia. De hecho, con la introducción de diversos planes y programas para mitigar o, al menos, reducir las emisiones de los buques, los puertos han empezado a adoptar una forma de manipulación de la carga más respetuosa con el medio ambiente.

Introduction

In the past years, the academic discussion surrounding the efficiency and productivity of seaport logistics has widened to include aspects that, very broadly put, relate to the generation and consumption of energy and resulting emissions. (He et al., 2017; Martínez-Moya et al., 2019; Spengler and Wilmsmeier 2019; Tichavska and Tovar 2019). The increasing interest in this topic is closely linked to raising energy costs as well as the prominence of the sustainable development discussion, as Vessels account for 90% of international transport and for 2.2% of worldwide emissions (Smith et al., 2015).

While the overarching issue of greenhouse gas (GHG) emissions and global warming can be thought as one of the key drivers that caused this broadening of academic interest, it should also be noted that the consumption of fossil fuels and therewith, the emittance of exhaust gases also have implications on a local scale. Apart from carbon dioxide (CO2), other gases such as nitrogen oxides (NOx), sulfur dioxide (SO2) as well as particulate matter (PM) are also emitted. While the effects of those aforementioned short lived climate pollutants are marginal on a global scale, they do have a substantial impact on a local scale with the predominant negative impact factor being the one on human health.

Policy makers aim at tackling this issue through a number of regulatory activities in urban areas. As for harbour logistics, cold ironing is perceived as an important measure that can be deployed to reduce air pollution in the vicinity of ports (Cullinane and Cullinane, 2019; Pettit et al., 2018). Cold ironing, sometimes also referred to as shore-to-ship power (SSP), is a technology where electric power is provided to berthed vessels from shore as opposed to the vessel itself generating electricity through auxiliary engines on board the vessel. By doing so, air pollution that might occur during the energy production process is geographically shifted to the location of the power plant. Power plants are usually located in less densely populated areas than ports. Also, the benefits of efficiency of scale in the energy production process can be leveraged when the process takes place in a power plant rather than through potentially many small auxiliary engines onboard a vessel. Analysis of subsidy programs for cold ironing as a potential strategy have been carried out (Wu and Wang, 2020) and even though cold ironing has a relatively high marginal cost when considered as a mere CO2 abatement technology (Wan et al., 2018), it is shown, that the benefits of cold ironing are substantial when considered as a way of reducing the external cost to the society in general and to the port cities in particular.

The objective of this thesis is to examine the efficiency and environmental aspects of seaport logistics taking a central focus on energy consumption and its implications. It aims to achieve this by addressing three interconnected research questions. Firstly, the thesis investigates whether considering energy-related variables and output disaggregation for measuring container terminal efficiency yields significantly different results. This analysis provides the foundation for understanding the relationship between energy consumption and overall efficiency in seaport operations. Building upon this, the thesis then explores the potential of cold-ironing as a means to reduce air pollution in ports. Through the assessment of the benefits of cold-ironing in the context of the Spanish port system, the thesis provides a perspective on its role in mitigating environmental externalities associated with onboard energy production. Finally, the thesis conducts an in-depth environmental valuation of in-port shipping emissions, considering different vessel types, in four Spanish ports. Through enabling a comprehensive understanding of the external costs associated with shipping emissions, his valuation provides insights into the areas where the implementation of cold-ironing facilities would yield the highest benefit. While it would have been desirable to already include emissions in the first chapter (emissions related to land side of the port), this was not possible due to a lack of available data.

Energy consumption and consequently emissions in container terminals have started to receive more attention. This is closely linked to the prominence of the sustainable development discussion and the increase in energy costs. Ports and container terminals are for once faced with the initial managerial decision on whether to purchase diesel or electrically powered equipment. Chapter 1, titled “Are output disaggregation and energy variables key when measuring container terminal efficiency?” and published in “Maritime Policy & Management” addresses the question of whether energy consumption variables and the disaggregation of output matter in the context of efficiency analysis of container terminals.

Starting with a discussion on theoretical concepts and variable selection for measuring the energy dimension of terminal efficiency, to the best of the authors knowledge, this is the first application of data envelopment analysis (DEA) comparing results with and without energy consumption, as well as differentiating productive outputs (dry and reefer container handling). The results reveal how the output disaggregation leads to substantially different efficiency scores and are a first step to show the relevance of output disaggregation and the inclusion of the energy variables as inputs in container terminal efficiency studies.

In terms of disaggregation of output, the argument in this chapter is that the commonly applied generalisation of measuring terminal throughput using an aggregate measure such as number of containers or number of TEUs might, under some circumstances, skew results of an efficiency analysis of container terminals. To illustrate this issue, this chapter analyses the efficiency levels of container terminals that handle a comparably high/low share of refrigerated containers. The hypothesis is that, despite being of standard sizes, standard (dry) containers and refrigerated containers vary significantly in their handling requirements, therefore, they should be considered as different outputs when it comes to measuring the terminal efficiency instead of being aggregated in a single measure. The matter is further intensified by geographical considerations, as the share of refrigerated containers in container terminals is, in general, higher in regions like Latin America than, for example, in Europe. A comparative analysis between those regions could potentially be confounded by a generally different share of refrigerated containers in container terminals in those regions.

In terms of the energy variables, as the review of the literature carried out highlights, this is the first paper that includes energy consumption as a production factor in a DEA container efficiency analysis, and it does so through two variables: electricity consumption (kwh) and diesel consumption (litres).

Obtaining the data for carrying out this research was a non-trivial undertaking. An online tool was developed that allowed terminal operators to insert energy consumption data. The collaboration with the United Nations Economic Commission for Latin America and the Caribbean (ECLAC) and stakeholders from the industry, made possible to collect data from more than 100 terminals. However, only 26 terminals were finally used in this research because of various data gaps that could not be filled in. For assessing whether further port related research is necessary on output differentiation and considering energy as an input, the available data was deemed to be sufficient.

A total of four models were computed to be able to make sound statements about the necessity of output differentiation and considering energy as an input: (1) A model where electricity and diesel are not considered as inputs and the aggregate of dry and refrigerated containers are considered as outputs, (2) a model where electricity and diesel are considered as additional inputs but still only the aggregate of containers are considered as outputs, (3) a model where dry and refrigerated containers are considered as separate outputs but electricity and diesel are not considered as inputs and (4) a model where dry and refrigerated are considered as separate outputs and electricity and diesel are considered as inputs.

The results reveal how the output disaggregation and inclusion of energy variables lead to substantially different efficiency scores. The in-depth look at the individual container terminals and their peers reveals that this change in efficiency scores is not just arbitrary but, in many cases, closely linked to the share of refrigerated containers that are moved through a given terminal.

The outcome of the model with energy as input and differentiated outputs was not substantially different from the one where energy was not considered as an input, but the output was still differentiated. This might be caused by the two variables being highly correlated. In conclusion, it can be argued that at least the differentiation of outputs needs to take place when conducting further research into port efficiency where terminals with greatly different shares of refrigerated containers are to be compared.

While chapter 1 stays within the organisational boundaries of the port, chapters 2 and 3 focus on the vessels in the port, their externalities and potential abatement through the technology of cold ironing. While it would have been desirable to also include emissions in chapter 1 (land side’s emissions), this was not possible due to the lack of reliable data.

Chapter 2, titled “Potential of cold-ironing for the reduction of externalities from in-port shipping emissions: The state-owned Spanish port system case” and published in “Journal of Environmental Management” provides insights into the potential of cold-ironing for the reduction of externalities originating from berthed vessels in Spain.

External cost derived from the emissions of CO2, NOx, SOx, and PM from berthed ships in the Spanish port system during 2016 were estimated providing a Spain-wide empirical evidence into where the highest externalities exist and where, on a port by port level, the introduction of cold ironing could yield the highest potential on reducing said externalities. Eco-efficiency parameters were also obtained. It is found that the population in the port city as well as the composition of traffic are key factors when the external costs are determined, and they should be considered when the investment decision about where cold ironing should be placed is taken.

It is important to note that the introduction of cold-ironing requires significant capital investment. On the shore side, infrastructure must be developed to supply electricity and convert the frequency of the national power grid (typically 50 Hz in Europe) to the frequency required on board vessels (usually 60 Hz). Similarly, vessels need to undergo substantial modifications to enable them to receive electricity from the shore. These investments are necessary to ensure the successful implementation of cold-ironing.

Ignoring the externalities associated with onboard energy production would lead to a significant underestimation of the overall cost of energy production onboard of vessels. Consequently, the economic viability of the technology may also be underestimated. Therefore, it is crucial to consider the full scope of external costs when evaluating the potential benefits of cold-ironing. Chapter 2 provides external cost figures for the entire Spanish port system which can be seen as prerequisites when aiming at internalizing external costs. In this way an informed decision can be made with respect to where the substantial investment in technology would lead to the greatest impact.

The calculations were carried out, following different methodological approaches which were selected based on an in-depth review of the approaches themselves and the relevant literature. External cost factors for NOx, SO2 and PM were obtained from BeTa which takes into account numerous health factors, the population of the respective (port) city and even other factors such as the negative impact of short lived climate pollutants on crops yield and structures. The external cost factor for CO2 were obtained from Delft and Infras (2011) who provided a high and low estimate.

This is the first time a Spain-wide analysis of external costs and the associated saving potential of cold ironing was conducted. The results in short were as follows: The combined Spanish overall external costs from both local and global effects of shipping emissions from berthed vessels were between 326 and 440 million Euro. Barcelona and Valencia exhibiting the highest external costs by a great margin, followed by Bilbao, Algeciras and Las Palmas.

Moreover, the eco-efficiency indicators such as "external cost per ship" and "external cost per hour" were calculated to provide more robust conclusions. Based on the overall findings and the eco-efficiency indicators, three main observations are made. Firstly, while the size of the population plays a significant role in estimating external costs, it is not the sole determining factor when comparing the eco-efficiency indicators. Secondly, the composition of traffic, including the types of vessels (e.g., cruise, bulk, container), also influence the external costs. Lastly, in order to fully comprehend sustainability in ports, more refined analyses are necessary. These analyses should incorporate eco-efficiency indicators and disaggregated figures based on vessel type.

While this article offered insights into many different aspects of external costs in the Spanish port system and their potential abatement through cold ironing, there were still things left for future research due to this article offering limited insights into the temporal dimension, as well as the external costs depending on the type of vessel which will both be addressed in the following chapter.

Chapter 3, titled “Environmental valuation of in-port shipping emissions per shipping sector on four Spanish ports” and published in “Marine Pollution Bulletin” provides external costs figures for ships berthed at four Spanish ports: Las Palmas de Gran Canaria (€74.4m), Tenerife (€20m), Palma de Mallorca (€19.5m) and Pasaia (€1.5m). This is done taking into consideration the need for more granular data recognized in the previous chapter. Hence, not only figures on a port-by-port level are provided but also figures per individual vessel type and port from a time-series perspective.

The external costs by shipping subsectors give more insights into the relationships between ship types and external costs. This has been done to correctly assign the responsibilities among the different shipping sectors inside a port and to better understand the potential benefits of implementing abatement technologies, such as cold ironing. Potential benefits from cold ironing were found to differ hugely among the different ports analysed.

The vessel types considered were general cargo vessels, container vessels, cruise vessels, refrigerated cargo vessels, roll-on-roll-off (RoRo) and others. This also has to be understood in the light of the relatively high capital cost for the implementation of cold ironing in ports and onboard of vessels. The aforementioned vessel types generally berth at different locations. This is due to the different requirements in terms of infrastructure. To approach the question where the highest benefit from the installation of cold ironing facilities might be achieved, it was found that the potential benefits from cold ironing differ hugely between the different ports.

The methodology deployed is based on the impact pathway approach (IPA), which has become a standard for estimating external costs associated with air emissions. The results and discussion section presents the estimated local external costs for each port using different models and scenarios. The variations between different models, namely NEEDS, CAFÉ and BeTa are analysed, and the BeTa methodology is chosen for further analysis due to negligible differences compared to other approaches.

The external cost of a vessel calling a port depends on a variety of factors. We found differences among ship types that cannot be explained only by the number of calls. Some are clearly related to the average time at berth whereas others can be associated to the characteristics of the vessel in question (i.e. vessel type, age, and so on). Liquid bulk carriers, for instance, usually are larger in average than container vessels or RoRo vessels. Vessel size, however, can also not explain the differences alone. Refrigerated vessels are generally small; however, they need to produce a relatively high amount of electricity onboard the vessel to keep the temperature in the cargo hold even at berth.

The vastly different patterns of external costs from different types of vessels make it necessary to look at the matter from a perspective of relative indicators rather than absolute values. Also, the eco-efficiency indicators "external cost per moored hour" as well as "external cost per vessel call" are computed per vessel type which is necessary to gain a more in depth understanding into the varying external costs that are associated with the different vessel types. It was found that the eco-efficiency indicators differ substantially between vessel types and ports. Reasons for those varying external costs can certainly be attributed to a number of factors such as average age and size of specific vessel types but also rather intrinsic factors associated with the vessel types themselves such as duration of cargo operations or energy consumption for hoteling.

This chapter highlighted the important role that the local effects of emissions, in terms of external costs, have on the cities and regions in the direct vicinity of a port. Although it has been shown that the external costs of a port are linked to the vessel type in question, the findings leave room for interpretation because there can also be great differences within one vessel type. Furthermore, the great potential for abatement technologies such as cold ironing is underlined by the findings in this chapter. It is now possible to assess to what extent such abatement technologies make sense and point towards the need of assessing the potential in each individual port per vessel type, as the differences are apparent.

To sum up, as this thesis has shown, ports have begun to explore ways to integrate environmental management into the local economy and society. These include performance measurement (eco-efficiency) through the environmental assessment (eg. emissions) in relation to economic factors (production) and supporting the design of policy instruments that have the eco-efficiency indicators into account. Indeed, with the introduction of a variety of plans and programs to mitigate or, at least, reduce emissions from vessels, ports have started to move to a more environmentally friendly way of handling cargo.

Chapter 1: Are output disaggregation and energy variables key when measuring container terminal efficiency?

1. Introduction

Two aspects have been widely ignored in container terminal efficiency research so far: the disaggregation of production outputs of container terminals and energy consumption variables. The former relates to the fact that terminal throughput, whether measured in TEU or number of containers, is an aggregated measure for handling a variety of goods with different characteristics and requirements inside a ‘standard size’ box. Despite being of standard sizes, standard containers and refrigerated containers vary significantly in their handling requirements. By way of example, whenever perishable commodities are transported, cooling is of essence to ensure their safe arrival at the destination. Reefer containers fulfil this role by maintaining a pre-set temperature within the container. Therefore, the input requirements throughout the handling in the terminal are different. Consequently, dry containers and reefer containers should be considered as different outputs when it comes to measuring the terminal efficiency instead of being aggregated in a single measure (total number of containers).

The relevance of reefer trades varies across different routes and therefore the proportion of dry/ reefer managed for terminals as well. Some of the highest shares of reefer containers can be observed on trade routes from Brazil to Europe and Asia, where these, depending on the season, can reach up to 35% and 30%, respectively. In trades between the United States and Northern Europe to Asia, the share of reefer containers ranges between 5% and 10%. On routes going to the Middle East from either the Mediterranean region or North Europe, the share is between 10% and 15% (Drewry Shipping Consultant Limited 2018).

Energy consumption and consequently emissions in container terminals have started to receive more attention in recent years (He et al., 2017; Martínez-Moya, Vazquez-Paja, and Gimenez Maldonado 2019; Spengler and Wilmsmeier 2019). The increasing interest in this topic is closely linked to the prominence of the sustainable development discussion and increasing energy costs. Ports and container terminals are for once faced with the initial managerial decision on whether to purchase diesel or electrically powered equipment.

Investment in cold ironing infrastructure and its use will have a further effect on energy consumption pattern in terminals.

Given these considerations, this paper applies Data envelopment analysis (DEA) to investigate if energy consumption variables and the disaggregation of output matter in the context of measuring efficiency in container terminals. To address this research question, this work is structured as follows. Section 2 reviews relevant research on container terminal energy consumption and provides a critical review on container terminal productivity and efficiency studies applying DEA. The DEA methodology, variables selected and models are described in section 3. Section 4 discusses the results of the DEA. Section 5 concludes.

2. Literature review

The body of literature on efficiency and productivity in the port sector in general and specifically in the container terminal sector has grown to a considerable size during the past few decades. This literature review does not pretend to give an exhaustive insight into all different approaches in productivity and efficiency studies in the port sector but focuses on a selection of articles on container terminal efficiency that are deemed to be useful to address the aforementioned research question (Table 1).

Two main methodological complementary approaches can be found in the literature: data envelopment analysis (DEA) and stochastic frontier analysis (SFA). DEA is a deterministic method based on linear programming (Charnes, Cooper, and Rhodes 1978), and Cullinane et al. (2006) identified high correlations between the results from DEA and SFA on port efficiencies. One advantage of applying DEA is that the functional form for the frontier does not have to be specified and thus results can be obtained with relatively small data sets (Tovar and Wall 2015). DEA has been the predominant methodology in this research area (Woo et al., 2011). Given existing data limitations and in order to show the relevance of previously not considered variables, this paper also applies DEA. Consequently, the following literature review will focus on the application of DEA at container terminal level (Table 1).

Two key challenges, when applying DEA or practically any quantitative methodology, are the selection of variables as well as the structure of the sample. It is generally agreed that the efficient allocation of land, labour, and equipment (see, for example, Dowd and Leschine 1990; Cullinane, Song, and Wang 2005; Guerrero and Rivera 2009) is at the very core of container terminal productivity and efficiency. This, in turn, leads to the question how land, labour, and equipment are represented in the previously conducted studies (see Section 3).

The literature review is divided in two parts. The first reviews the literature on the emerging relevance of energy efficiency and energy consumption in container terminals, even if not necessarily conducted in the context of efficiency or productivity analysis. The second critically reviews previous efficiency studies at container terminal level applying DEA.

2.1. Energy Consumptions and Energy Efficiency Studies in Terminals and Ports

Energy consumption and energy efficiency in the context of container terminals have so far been addressed on either operational level, on terminal level or on policy level. To the best of the knowledge of the authors, no approach has been shown where energy variables were considered an input in a DEA or SFA model, the only exception being Guimaraes et al. (2014), who measure environmental efficiency.

The research covering the operational level, stretches from individual equipment, routing problems to new approaches to reduce energy consumption or even produce energy in a terminal. By way of example, Yang et. al. (2013) analysed the monetary as well as CO2 saving potential of electric rubber-tired gantry cranes (RTGs). These authors mention a potential reduction in energy consumption of up to 60% through technological change. In the light of the apparent difficulties of identifying the actual consumption of equipment, Hangga and Shinoda (2015) proposed a methodology for obtaining energy consumption of straddle carriers. He et. al. (2015) discussed in their paper a novel approach to the yard crane scheduling problem where timesaving was not considered the ultimate goal but rather a trade-off with energy-saving. Budiyanto et. al. (2018) analysed the effect roof shades of refrigerated containers have on energy consumption pattern and estimated the savings to be about 17%. Van Duin et al. (2018) approached the question of how energy peaks of reefer racks can be reduced and found substantial opportunities for reducing energy consumption by applying peak shading.

While those findings and approaches underline the importance of research in the field of energy consumption and efficiency in the terminal sector, they provide very limited insights as to how an approach could look like that covers an entire terminal, let alone multiple terminals. It shows however, that energy consumption in terminals is difficult to be modelled accurately as many different external as well as internal factors play an important role.

Multiple approaches to coordinated collection and analysis of energy consumption data can be observed. Wilmsmeier et. al. (2014) collected data from 13 terminals in Argentina, Chile, Paraguay and Uruguay. This was done against the background of substantial traffic of refrigerated containers that are being moved through the terminals of those countries. Following an activity-based approach, they reported on energy consumption patterns in terminals in those countries. However, the findings were presented on a rather descriptive level without offering insights into the potential ramifications on productivity or efficiency. Also, the kind of comparison of diesel and electricity consumption that was carried out made it necessary to convert those energy sources to the same unit. It was not accounted for energy conversion efficiency. In contrast, DEA allows to have the inputs electricity consumption as well as diesel consumption in their native unit of measurement.

Wilmsmeier et. al. (2014) found that the energy consumption patterns differ vastly between terminals when a differentiation of dry and reefer TEU is carried out. Also, on equipment level, it was found that energy consumption can hardly be seen as mere function of the operating hours of the equipment which contradicted some modelling approaches like the one of Geerlings and van Duin (2011). Wilmsmeier and Spengler (2016) continued to build upon Wilmsmeier et. al. (2014) and reported among other things on the differences in consumption patterns of small, medium and large terminals. They also observed great differences in consumption patterns across terminals from different countries. This, in turn, raises the question if energy in and by itself should be considered an input in the analysis of terminal productivity and efficiency.

Azarkamand et al. (2020) introduced an online tool, similar to the one developed by Wilmsmeier and Spengler (2016), for calculating carbon footprints in ports.

Martínez-Moya et. al. (2019) followed a similar, activity-based, approach for the NCTV terminal of the port of Valencia. They report that roughly 50% of the electricity consumption in the terminal can be allocated to refrigerated containers. This figure as well as the other findings are aligned with the findings presented by Wilmsmeier et. al. (2014) and Wilmsmeier and Spengler (2016).

Apart from the more practical approaches, certain publications address mostly the matter of policy implications. Acciaro et. al. (2014) describe the role port authorities could have for energy management based on a case study for the port of Hamburg and the port of Genoa. They found that at least in Hamburg the city seems to be more of the driving force towards more energy efficiency while in Genoa the port authority is taking this role. Wilmsmeier (2020) does similarly report that the Colombian government has adopted the methodology described by Wilmsmeier et. al. (2014) and Wilmsmeier and Spengler (2016).

Iris and Lam (2019) carried out a review of the currently present operational strategies, technologies as well as energy management systems. In terms of operational strategies, they described two relevant options: (1) optimization of operations such as quay crane assignment and reduction of port stay time and (2) peak shaving as for example also described by van Duin et al. (2018). With respect to technologies, following aspects are mentioned: (1) cold-ironing, referring to supplying electricity to vessels from the shore side (2) improvements in the equipment as well as alternative fuels for equipment (3) more energy efficient handling of reefer containers, in particular shading as also mentioned by Budiyanto et. al. (2018) and (4) improvements in lighting through, by way of example, LED lamps. In terms of energy management, Iris and Lam (2019) mention (1) measuring as well as estimating of energy consumption which can be seen as a foundation for improvements and (2) the energy supply which could preferably be renewable or cleaner than conventional energy sources. Also mention is made of (3) smart grids as well as (4) policy frameworks for energy management.

Consequently, the further understanding of energy consumption patterns as part of productivity and efficiency analysis are of increasing relevance in the port industry.

2.2. Productivity and Efficiency Studies in Container Terminals: a critical view

It is paramount to point out that in numerous existing studies on port and terminal efficiency not all authors clearly define the unit of analysis. Frequently, the terminology "container port" is used as synonymous for "container terminal", despite the fact that each corresponds to different realities[1]. Additionally, it can be observed that the unit of analysis is referred to as "container port", but the sample includes ports that have significant movement of other cargo types (e.g. general cargo or even bulk cargo) (e.g. Gonzalez and Trujillo, 2009). Either of the two mentioned inaccuracies allows for questioning the actual comparability and validity of these studies. The research in this paper is specifically interested in analysing container terminals as they are one specific decision-making unit (DMU) (Yip et al., 2011). Thus, only those papers which verifiably define the unit of analysis as container terminal are included in the literature review. Throughout the text, the term terminal[2] always refers to container terminal, unless stated otherwise.

Obtaining reliable and sufficient data has been (Neufville and Tsunokawa, 1981) and continues to be a common challenge in the study of productivity and efficiency in terminals. Pjevčević et. al. (2011) as well as Yip et al. (2011) argue for the importance of a clear DMU definition, when setting up their simulation exercise. Most of the here reviewed papers struggled with data availability as well (e.g. Yang and Yip, 2019). Bichou (2011) reported that he had to reduce the original sample size from 50 to 10 because of data availability issues. Lu and Wang (2012) used data from 31 terminals but were limited in the selection of input variables.

The authors identified three works that analyse productivity (Wilmsmeier et al., 2013, Yang and Yip, 2019 and Chandrasekhar and Nihar, 2021), the majority of of studies apply DEA-CCR and DEA-BCC (Table 1), Munin (2020) being an exception applying also FDH. By way of example Lu and Wang (2012) analysed the operating efficiency of 31

---

[1] As Cullinane and Wang (2004) recognized: "This study initially intended to investigate individual container terminals. However, data sources often reported the required data at the aggregate level of the whole port, … In these cases, the input and output of a port are defined as the aggregation of the input and output of individual terminals within the port. It is important to recognise, however, that such aggregation may prove problematic in reflecting the true production efficiency of the individual terminals within the same port"

[2] The efficiency of terminals with multipurpose facilities (those handling also non-container cargoes) is out of the scope of the present paper but the interested reader could be found some example in Chang and Tovar (2014ab and 2017ab).

major container terminals in east-Asia, namely China and Korea. Their study was strongly following Cullinane et al. (2005) and the resulting findings were likewise aligned with those of Cullinane et al. (2005). By way of example, they found that terminals with a throughput of more than 0.5 million TEU show constant returns to scale, while terminals with a throughput of less than 0.5 million TEU show increasing returns to scale. Also, it should be noted that the variable selection of Lu and Wang (2012) was also influenced by Cullinane et al. (2005) in the sense that they did not consider labour as an input which stands in contrast to the findings of Itoh (2002).

Rios and Maçada (2006) analysed the efficiency of container terminals of the Mercosur trade bloc. With respect to the input variables, it should be noted that an arbitrary aggregate is used for the number of yard equipment. This has to be seen critical, as yard equipment can range from a simple forklift to elaborated equipment such as Rail-Mounted Gantry Cranes (RMGs). Considering such an aggregate as input would mean that, ceteris paribus, a terminal with nine RMGs and one forklift is as efficient as a terminal with one RMG and nine forklifts.

Despite the fact that Yang and Yip (2019) find that container efficiency changes have not been studied sufficiently in Asia, most recent studies focus on that region, Middle East or India, Wiegmans and Witte (2017) and the two studies from Bichou (2011, 2013) being exceptions. In several cases an application of almost similar input and output variables can be observed.

Mokhtar (2013) applied DEA to six major container terminals in Malaysia. This work excludes labour, without given any arguments for the decision. A remarkable feature in his input selection is the one of Quay Crane Index, which was defined as the product of the number of quay cranes and their average lifting capacity. Given common weight restrictions for standard ISO containers, considering lifting capacity of cranes a relevant input for terminal efficiency or productivity is hard to justify. Still, accounting for different types of cranes such as mobile cranes can be a challenge. In this document the approach of Wilmsmeier et al. (2013) is followed as described in subsection 3.2.3.

Sharma and Yu (2010) proposed a decision tree based DEA and illustrated its application to the container port industry. The authors argue that the labour was not included due to the unavailability of data and because they think it is undesirable to follow the suggestion of Tongzon (2001) to make some proxy estimation, as this may give biased results. What the author seems to forget is that their decision to ignore labour as an input also produces biased results.

Few papers address productivity and efficiency in terminals in other regions. Dias et al. (2012) assess the efficiency of 10 Iberian container terminals in 2007 applying a recursive DEA model. Almawsheki and Shah (2015) analysed 19 container terminals in the middle eastern region, aggregating yard equipment similar to Rios and Maçada (2006).

Lim et al. (2011) proposed a method based on the idea of the context-dependent DEA. To illustrate the proposed methodology, they evaluate the relative efficiency of 26 Asian container terminals in the year of 2004. In the empirical application they included a brief summary of input and output used for some previous DEA studies, they do not explain what the reasons behind their election of input and output are. It should be noted that they do not consider labour as an input.

The inclusion or omission of labour variables has stimulated controversial discussions. Itoh (2002), was able to obtain rich data for eight terminals. In a similar approach to the research conducted in this research, regarding the relevance and representation of labour, Itoh (2002) analysed container port efficiency in Japan and the effect labour as an input variable on the obtained scores. Applying DEA, he was able to show how labour as an input changes the obtained efficiency scores substantially and argued that labour "is a key input in the port production and cannot be totally neglected.". Notwithstanding these results and to the best of the authors´ knowledge, only four later works (Rios and Maçada, 2006; Wilmsmeier et al., 2013, Wiegmans and Witte, 2017; Park, et al., 2020) include labour variables in the analysis of container terminals applying DEA.

The arguments for omitting labour variables vary. Almawsheki and Shah (2015) justified their decision to omit labour by referencing ten other studies that also did not use labour. An approach that actually does not justify their decision. Yang and Yip (2019) present three questionable arguments for the omission. They argue for a "fairly close" relationship between the number of workers and the number of gantry cranes, which makes a separate inclusion of this input unnecessary, however they ignore that container terminals are much more than ship-to-shore operations. Further, they mention low reliability of port statistics, due to outsourcing, without providing evidence. Finally, they argue, citing Notteboom et al. (2000), that infrastructure and machineries inputs reflect a more accurate configuration of the ports than labour.

Bichou (2011) studied container terminal efficiency applying a two-stage supply chain DEA model. He criticized existing publications for inconsistent findings as well as trade-offs that are made in the variable selection. To approach those perceived shortcomings, Bichou (2011) and Park et al. (2020) split container operations in three sub-processes: the quay, the berth and the gate with their respective inputs and outputs. This high level of disaggregation requires naturally a high number of detailed data on the terminals under study. While these authors were able to obtain some of them, only Park et al. (2002) include labour as an input. While Bichou (2011) argued that not including labour was due that each configuration of generic operating typologies (for both quay and yard operating sites) in the different sub-processes would require “a corresponding set of capital and labour mix, and thus no cost or labour data is required [in this study]”. However, Park et al. (2020) are able to contest this issue.

Kuo et al. (2020), while considering the commonly used input variables, is the only work that uses the number of vessel calls as an output variable. Measuring container terminal output in this way might be questionable as the number of vessels which call or arrive at a particular port at any given time is a heterogeneous measures as it does not take differences in vessel size into account. Li et al. (2021), also using the commonly applied variables, applies a super-efficiency data envelopment analysis (SEDEA) approach. This approach allows for categorizing and ranking the efficiency of container terminals more comprehensively.

To sum up, the literature review reveals that no previous efficiency study applying DEA, has included energy variables or disaggregation of output at terminal level.

Second, a detrimental development can be observed in the case of labour as an input variable over time. Only four works include labour variables in their models. Wiegmans and Witte (2017) provide the most detailed approach to this issue using weekly worked hours as an input variable. The broad omission, of labour variables in the majority of the works ignores significant inputs in container terminal operations.

Third, with the only exception of Park et al. (2020), who disaggregate the output in transhipment, inbound and outbound container, none of the existing studies addresses disaggregation of output by container type (dry and reefer), an approach that allows to analyse possible different input needs and productivity depending on the mix of containerised cargoes in a terminal.

Consequently, this work addresses the three identified gaps in literature, aiming to show the relevance of energy variables and disaggregation of outputs, based on a data set that also includes the relevant dimension of labour as an input.

Table 1: Summary papers on container terminals applying DEA and use of variables

Paper	Region	Number of Terminals	DEA Model	Output	Input	Labour	Energy	Output disaggregation (dry/reefer)
Itoh (2002)	Japan 10-year period (1990-1999)	8	Window DEA-CCR Window DEA-BCC	● Throughput (TEU)	● Container terminal area (m^2) ● Container berths (number) ● Gantry cranes (number) ● Workers (number)	YES	NO	NO
Rios and Maçada (2006)	Latin America 3-year period (2002-2004)	23	DEA-BCC	● Throughput (TEU) ● Avg. number of containers moved per hour per ship	● Cranes (number) ● Berths (number) ● Terminal Area (m^2) ● Employees (number) ● Yard Equipment (number)	YES	NO	NO
Sharma and Yu (2010)	World Wide (not available)	70	Decision tree-based DEA	● Throughput (TEU)	● Quay cranes (number) ● Transfer cranes (number) ● Straddle carriers (number) ● Reach stackers (number) ● Quay length (m) ● Terminal area (m^2)	NO	NO	NO
Bichou (2011)	World Wide 7-year period (2002-2008)	10	Supply Chain DEA-BCC	● Export TEUs ● Yard dwell time ● STS crane move/hour	● Gate lanes (n.a.) ● Cut-off time (n.a.) ● Yard stacking index (n.a.) ● Free yard storage (n.a.) ● STS crane index (n.a.) ● LOA/max draft (n.a.)	NO	NO	NO
Dias et al (2012)	Iberian Peninsula (2009)	10	Recursive DEA	● Throughput (TEU)	● Total yard equipment (number) ● Quay length (m) ● Terminal area (m^2) ● Container cranes (number)	NO	NO	NO

Paper	Region	Number of Terminals	DEA Model	Output	Input	Labour	Energy	Output disaggregation (dry/reefer)
Lin et al. (2011)	Asia (2004)	26	Context-dependent DEA	● Throughput per berth (TEU)	● Berth (number) ● Quay length (m) ● Total area (m^2) ● Gantry cranes (number)	NO	NO	NO
Lu and Wang (2012)	China and Korea (2008)	31	DEA-CCR DEA-BCC DEA-Super Efficiency	● Throughput (TEU)	● Yard area per berth (n.a.) ● Quay crane per berth (n.a.) ● Terminal crane per berth (n.a.) ● Yard tractor per berth (n.a.) ● Berth length (n.a.) ● Water depth (n.a.)	NO	NO	NO
Bichou (2013)	World Wide 7-year period (2004-2010)	60	DEA-CCR DEA-BCC	● Throughput (TEU)	● Terminal (m^2) ● Maximum draft (m) ● Total quay length (m) ● Quay crane index (TEU) ● Yard-stacking index (TEU/1000 m2) ● Trucks & vehicles (number) ● Gates (number)	NO	NO	NO
Mokhtar (2013)	Peninsular Malaysia 8-year period (2003-2010)	6	DEA-CCR DEA-BCC	● Throughput (TEU)	● Total terminal area (m^2) ● Maximum draft (m) ● Berth length (m) ● Quay crane index (n.a.) ● Yard-stacking index (n.a.) ● Vehicles (n.a.) ● Gate lanes (number)	NO	NO	NO
Wilmsmeier et al. (2013)	Latin America and the Caribbean and Spain (2005-2011)	20	DEA-CCR DEA-BCC Malmquist	● Throughput (TEU)	● Labour (number of employees) ● Terminal area (m^2) ● STS equivalent (number)	YES	NO	NO

Paper	Region	Number of Terminals	DEA Model	Output	Input	Labour	Energy	Output disaggregation (dry/reefer)
Almawsheki and Shah (2015)	Middle East (2012)	19	DEA-CCR DEA-BCC	• Throughput (TEU)	• Terminal area (Ha) • Quay length (m) • Quay cranes (number) • Yard equipment (number) • Maximum draft (m)	NO	NO	NO
Wiegmans, and Witte (2017)	Mostly Germany, Belgium and Netherlands	44	DEA-CCR DEA-BCC	• Handling capacity (TEU) • Throughput (TEU)	• Working hours (week) • Terminal area (m^2) • Stacking Yard (TEU) • Quay Length (m) • Draught (m) • Cranes (number) • Reach stackers (number)	YES	NO	NO
Yang and Yip (2019)	Asia (2000-2007)	23	Malmquist	• Throughput (TEU)	• Berth length (m) • Terminal Area (m^2) • Crane Capacity (Ton)	NO	NO	NO
Munin (2020)	(Asia)	38	DEA-CCR DEA-BCC FDH	• Throughput (TEU)	• Berth (number) • Berth length (m) • Depth (m) • Terminal area • Yard gantry cranes (number) • Ship-shore and quay gantries (number).	NO	NO	NO
Kuo, Lu, and Le (2020).	Vietnam (2017)	53	DEA-CCR DEA-BCC	• Tons • Ship (calls)	• Total terminal area (m^2) • Terminal length (m) • Equipment (number)	NO	NO	NO

Paper	Region	Number of Terminals	DEA Model	Output	Input	Labour	Energy	Output disaggregation (dry/reefer)
Park, Lee, and Low (2020).	South Korea (2014-2018)	9	Two-stage parallel network DEA DEA-CCR	● Outbound (TEU) ● Inbound (TEU) ● Transhipment (TEU)	● Wharf length (m) ● Employees (number) ● Yard area (m^2) ● Quay cranes (number) ● Yard cranes (number) ● Supporting machines (number) ● Vehicles (number) ● Level of service (n.a.) ● Market exposure (number of operating years) ● Planned throughput Capacity (n.a.)	YES	NO	NO
Chandrasekhar & Nihar (2021)	India (2015-2018)	26	Malmquist	● Throughput (TEU)	● Draft (m) ● Quay Length (m) ● Quay Cranes (number) ● Yard equipment (number) ● Yard Area (Ha)	NO	NO	NO
Li, Seo, and Ha (2021).	China 2018	20	Super-efficiency DEA	● Throughput (TEU)	● Berth length (m) ● Yard area (m^2) ● Bridge Crane and RTG (number) ● Dock front water depth (m)	NO	NO	NO
Present paper	Worldwide (2013)	26	DEA-CCR DEA-BCC	● Throughput container (number of boxes) ● Throughput dry container (number of boxes) ● Throughput reefer container (number of boxes)	● Labour (number of employees) ● Berth length (m) ● STS equivalent (number) ● Electricity (kWh) ● Diesel (litres)	YES	YES	YES

Note: DEA = Data Envelopment Analysis; FDH = Free Disposal Hull; TEU= Twenty feet Equivalent Unit; LOA = Length overall; Not available (n.a.)

Source: Authors

3. Methodology

3.1. Data Envelopment Analysis (DEA)

Efficiency and productivity are often used interchangeably (Wang and Cullinane, 2015), however they are two different but related concepts. Productivity is defined as the comparison between outputs over inputs, thus it can be asserted that the higher the rate between outputs and inputs the higher the productivity level. Besides, technical efficiency is defined as the maximum output that can be obtained from a given amount of input or the minimum input to achieve a given amount of output, depending on the output/input orientation of the model.

Therefore, both concepts are defined in terms of a comparison of two components (inputs and outputs) and are equivalent if one component (inputs or outputs) does not change. However, when both change, what is the usual situation in the real world, there are important differences between both that could produce situations where not always an improvement in efficiency comes with an improvement in productivity.

Moreover, to estimate technical efficiency it is necessary to estimate the best practice frontier whereas productivity could be calculated without it. If the frontier is estimated, it is possible not only to identify productivity changes but also it is also possible to decompose the productivity change to identify whether this originates from efficiency change and/or technological change.

Given the previous definitions, measuring the efficiency or productivity of firms could be considered to be a trivial mathematical task. However, the production frontier of an industry is virtually never known, but using a variety of parametric and non-parametric approaches an efficient (best practice) frontier can be estimated.

Container terminals in the context of DEA are referred to as one decision making unit (DMU). This implies that they are individual firms striving to achieve an objective. While the authors recognize that other possibilities exist, the authors assume that the objective can either be to maximize throughput (output) from a certain level of input or to achieve a certain level of output with as little input as possible. The following equation shows an input-oriented CRS DEA model:

$\min \theta$ (1) s.t.:

$-y_i + Y\lambda \geq 0;$

$\theta x_i - X\lambda \geq 0;$

$\lambda \geq 0.$

This equation is the most commonly solved envelopment form of the problem. The scalar θ is representing the efficiency of the container terminal and λ is a column vector "*that describes the percentage of other companies, and is used for constructing the efficient company. X and Y are the companies' input and output vectors, and [x_i] and [y_i] are the inputs and outputs of the company that is being evaluated*" (Pérez-Reyes and Tovar, 2009). The calculations were carried out in Python with the help of numpy.

3.2. Data Source and Variable Selection

Reliable and sufficiently detailed data has been identified as a key challenge in the reviewed literature on terminal efficiency/productivity. Data used in this work, originate from a concerted effort that was led by the United Nations Economic Commission for Latin America and the Caribbean (UNECLAC) in collaboration with Hochschule Bremen and stakeholders from the industry as well as governmental entities across Latin America (Wilmsmeier and Spengler, 2016; Spengler and Wilmsmeier, 2019) and was collected through UNECLAC/HS Bremen port productivity and efficiency surveys. One challenge of the collected data, is the level of fragmentation. While data was collected from more than 100 terminals, it was not possible to fill in missing values in all dimensions in order to create sufficiently large panel data, which would be required to make sound statements from a time series perspective while maintaining the high number of variables.

The data set for this research comprise 26 terminals for the year 2013. Given the nature of the research question, it is key to work with data that comply with the expected level of detail for all selected input and output variables as the research is focusing on a structural discussion of data requirements in terminal efficiency studies. While more recent data in general is available for some variables, particularly detailed data on energy consumption, which includes the composition of energy source is difficult to obtain. However, more recent data cannot be thought to increase the validity of this research. All terminals under study are specialized in container handling, but with varying functions within the container terminal system. Their functions vary between import/export, hybrid and transhipment terminals. The data set covers a wide array of terminals, reaching from rather small terminals in developing countries to large terminals in developed countries. Table 2.1 and Table 2.2 depict the maximum, minimum, standard deviation, average and median of the selected variables. The distributions of some of the variables are somewhat skewed considering a comparison of the median and the average. It is worth pointing out that the relation of dry to reefer containers tends to differ significantly between terminals. The terminals situated in Latin America have a generally higher share of reefer containers, which was to be expected given the different characteristics of trade routes.

Table 2.1: Descriptive Statistics of output variables

	Throughput (number of boxes)		
	Total Container	Dry Container	Reefer Container
Minimum	75989	50877	913
Maximum	2206438	1967770	238668
Standard Deviation	428393.98	381242.16	48520.12
Median	425003	412986	15064
Average	496831.96	460293.15	36538.81

Note: Total container represents the aggregated output variable, Dry and Reefer container represent the disaggregated output variables.

Source: Authors

Table 2.1 depicts the descriptive statistics of the chosen output variables. A longer discussion as to why those variables were chosen, is provided in the following subsection. Total container throughput is equal to the sum of dry containers and reefer containers at individual terminal level. Within the sample the share of reefer containers in relationship to dry container handling varies. Some terminals handle close to no reefer containers while others handle a very substantial amount of reefer containers.

Table 2.2: Descriptive Statistics of input variables

	Diesel (Litres)	Electricity (kWh)	Labour (number)	Total Berth Length (m)	Ship-to-Shore Crane Equivalent (number)
Minimum	570000	1724029	216	320	3
Maximum	8284658	46761686	4878	2884	25
Standard Deviation	1796396.36	8999166.98	878.65	624.58	4.26
Median	2718971	13509486.5	573	948.5	6.5
Average	2767282.35	14103842.15	778.23	1081.88	7.19

Source: Authors

Table 2.2 depicts the descriptive statistics of the chosen input variables. Given the diverse sample, it is not surprising that the input variables show a relatively large standard deviation as well as a large spread between the maximum and minimum.

As mentioned above, a common and almost generally accepted argument in the field of productivity and efficiency analysis in ports and terminals is the one of land, labour and equipment being the key deciding factors (Dowd and Leschine, 1990; Roll and Hayuth, 1993). The chosen input variables represent the physical characteristics, technology, and the type of operation in the terminals. Different to existing studies the authors include the energy consumption as an input variable. The following subsections (1) provide the rational of the selected variables, and (2) specify insights on required or unacceptable trade-offs when choosing these.

Labour

As exemplified in the literature review, only few works include direct labour variables. However, all of them recognize this lack as an important limitation of both the investigation and conclusions. Indeed, it is well-known that excluding labour input from the model may lead to a biased estimate of terminal efficiency if labour and capital are not perfectly complementary (Chang and Tovar, 2021). The latter assumption (perfect complementarity) means that all container terminals follow a Leontief technology that implies the factors of production will be used in fixed (technologically predetermined) proportions, as there is no substitutability between factors, which is implicit when labour is excluded from the analysis. To the best knowledge of the authors this relationship (perfect complementary between labour and capital in this industry) has neither been demonstrated in previous port studies nor can it easily be deduced, considering that the relationship between capital and labour can be affected by various factors, including the technological one. Therefore, we conclude that the inclusion of labour is of utmost relevance to avoid biased results.

In those studies, where labour variables are included, the total number of employees is the most common variable. Only very rarely, the hours worked (Wiegmans and Witte, 2017) or labour cost can be found as input variables. It certainly can be argued that labour cost would be the most favourable input variable, since it would capture the rather fine differences between different equipment configurations, automatization, and labour conditions, as well as the more apparent differences between blue-collar and white-collar workers. At the same time, introducing a monetary variable also comes with caveats: if data from various periods is to be used, it must be deflated and, if data from a variety of countries is used, it must be expressed in a common currency. Following Wilmsmeier et al. (2013), the authors include the total number of employees of the container terminals as an input as no sufficient salary data is available to the authors.

Land

The factor of land is usually represented by variables such as berth length, terminal size, or terminal storage area. Each of them having specific advantages and disadvantages.

Total berth length is often calculated as the sum of the lengths of a variety of berths (e.g. Yang and Yip, 2019), which can give a somewhat skewed representation of the actual input. By way of example, one terminal could potentially have one berth of approximately 200 metres while another terminal could have 2 berths with a length of 100 metres per berth. The former would be able to accommodate significantly larger vessels while the latter could not. An advantage of using total berth length is that a very general understanding of this input exists. While total berth length indisputably is a measure for the available space in a container terminal to which ships can be moored, the actual berth capacity will depend on the distribution of this length in relation to the number of berths in the terminal.

Terminal storage area and terminal size cannot be considered as intuitive input factors. Terminal size might yield different interpretations, depending on what might be considered as the terminal area. By way of example, parking areas for employees might be part of the terminal or not, so could the area where terminal buildings are placed. These challenges could be overcome, e.g. if the exact size from a potential concession contract would be available. Though, this exact information is not available in the dataset of this research.

Terminal storage area also might not accurately capture land as an input. Measuring storage area in a two-dimensional way omits the fact that operations in a container terminal are rather three than two dimensional, meaning that the efficient use of the surface area at hand also depends on the stacking height of containers. Further, stacking height might differ in different areas of the terminal.

One might argue that these issues are possible to overcome if primary data are collected and a very clear definition of variables is provided. Still, it is believed that the person who will provide the data has very little incentive to review the size of the terminal or storage area according to the variable definition and will rather provide the values that are readily available.

Given the described restrictions of land input variables in combination with actual data availability, the authors decided to include total berth length in metres as a proxy input variable to the model, even though certain points can be made in favour of including a measure of area rather than length.

Equipment

It can be argued that this input factor is the most challenging to accurately represent in the model (Spengler and Wilmsmeier, 2019), given the variety of different possibilities to equip any given terminal. By way of example, the inclusion of only one particular kind or group of equipment, such as straddle carrier (SC) or rail mounted gantry crane (RMG), might lead to a restricted reference set. An aggregation of a variety of different equipment would also be difficult to justify as one would be required to argue that the overall aggregated number of equipment is in some way, shape or form related to the objective of a given terminal. An introduction of monetary variables for equipment and its operation, could be a future option, but would have the similar caveats as mentioned in the case of labour.

While it would be desirable to account for different types of equipment as well or potentially even cluster the terminals by operational layout, this is not feasible with the available data and the limited sample size. Hence, the decision is made to restrict the equipment variable to berth side operating equipment, represented by the number of quay cranes equivalent. This variable is derived as a weighted aggregation (summation) of mobile and ship-to-shore cranes following the approach of Wilmsmeier et al. (2013).

Energy

A unique feature of this research is the inclusion of energy consumption variables, namely diesel and electricity, as an input. Energy can be referred to in different ways. The most intuitive way is to treat the various energy sources in their own unit of measurement since a conversion of electricity (kWh) and diesel (litres) to a common energy related unit such as Joule or Watt is all but trivial.

Other potential measures could be energy expenses. While energy expenses can be thought to be rather a desirable measure for the energy input, it has to be acknowledged that such data are difficult to obtain and bear similar challenges in measurement and comparability as other monetary measures.

Based on the described challenges the authors include two variables for representing energy consumption: diesel (litres) and electricity (kWh). It should also be noted that an initial data review checked for other potential energy sources such as petrol, liquefied natural gas (LNG), liquefied petroleum gas (LPG) and compressed natural gas. These energy sources are either not used in the terminals or used in negligible quantities and thus were excluded from the model.

Outputs

Roll and Hayuth (1993) argue that terminals provide a significant variety of outputs. Including, not only “the quantities and the variety of cargoes handled”, but also “the types of ships serviced, the interchange with land transport modes, the additional services rendered (e.g. interim warehousing) ...". In the majority of studies on container terminals this output is reduced to the measure of TEU or at best number of containers handled.

The outputs of a container terminal would actually best be represented by a rather high level of disaggregation, since the activities related to handling a container in a terminal will vary according to the combination of the type of trade (e.g. import, export, or transhipment), the specific container types, (e.g. refrigerated, open top, dry), the size (e.g. 20 or 40 foot) and the condition (e.g. full or empty). For a discussion on the differences of energy consumption between dry and reefer containers see Wilmsmeier and Spengler (2016).

Such level of disaggregation would be ideal; however, it would require an overwhelmingly large number of DMUs which is not available in this case. Since total energy consumption is considered as an input and based on the difference of the energy consumed by full refrigerated containers in comparison to other container types, the decision is made to disaggregate the output only by the refrigerated or dry property of a container. In some models an aggregate of container throughput will be used for the sake of comparison. In this respect, reefer containers as well as dry containers are measured in the unit of *box* rather than TEU.

3.2. The Models

To address the set-out research question a sequence of four models is built. The variables included, in order to investigate the impact of container terminal output disaggregation and the inclusion of energy consumption variables as an additional proxy to the traditional input factor proxies are: total berth length, ship-to-shore crane equivalent and labour.

Table 3 summarises the estimated models, indicating the respective input and output variables. By way of example, in model 1, labour, berth length and STS crane equivalent are considered as input variables. As output variable, only total container movements is considered.

Table 3: Models with their respective inputs and outputs

		Inputs	Outputs

	Output disaggregation	Labour	Berth Length	STS Crane Equivalent	Electricity	Diesel	Dry	Reefer	Total
Model 1		√	√	√					√
Model 2		√	√	√	√	√			√
Model 3	Yes	√	√	√			√	√	
Model 4	Yes	√	√	√	√	√	√	√	

Source: Authors

For each model, the variable return to scale (VRS) as well as constant return to scale (CRS) are estimated. The matter of orientation is not straightforward. As shown in the literature review, terminals are said to follow two approaches. Either terminals seek to maximize output, given a certain level of input, or terminals seek to minimize inputs, given a certain level of output that they might be able to anticipate. Experience shows that terminal operators generally try to increase market share, particularly in emerging markets, rather than maintaining a given share with as little input as possible. Therefore, the authors argue that the terminal operators included in this research rather seek to maximize output.

Due to data confidentiality agreements with the terminals, the specific names of the terminals and their operators are not disclosed. The names are replaced by the ISO 3166-1 alpha-3 code of the country where the terminal is located, followed by a single number to differentiate various terminals within the same country.

The data set comprises container terminals from different countries that to the authors' belief are comparable as they belong to the same population. However, given that the sample includes import/export, hybrid and transhipment terminals the authors applied the non-parametric

Mann–Whitney U (MW) to test the null hypothesis that the samples come from the same population (Table 4)[3].

Table 4: Non-parametric Mann–Whitney U test

	Z	P(1)	P(2)	Statistic U
Model 1	-1.53	0.063	0.126	28.5
Model 2	-1.01	0.1562	0.3125	36.5
Model 3	-0.88	0.1894	0.3789	38.5
Model 4	-0.65	0.2578	0.5157	42

Note: with na=21, nb=5, (1) one-tailed probabilities, (2) two-tailed probabilities, U tabulated ($\alpha = 0.05$) = 22

Source: Authors

4. Analysis and discussion

This section discusses the results of the DEA model estimation. Table 5 depicts the efficiency scores for CRS and VRS models, with and without aggregation of outputs (models 1 to 4).

An initial finding, due to the nature of DEA, is that both CRS and VRS models yield higher efficiency scores if they include a greater number of dimensions; read model 4 with output disaggregation and including energy variables (Table 5). Likewise, the generally higher efficiency scores of VRS in comparison to CRS models are owed to the applied methodology.

Even though, there are certain variations that are inherently related to the addition or omission of variables, other relevant results can be discussed. One of these cases are the scores for

---

[3] All calculated p values are greater than 0.05, meaning that the null hypothesis cannot be rejected on those bases. Given that the approximation of U by the normal distribution is best when both populations are equal or greater than 10, it is recommended to work with the tabulated value for respective sample sizes. In this respect, the statistic U is never below the tabulated value, indicating against this background the null hypothesis cannot be rejected, either. This indicates that there is no difference in the computed efficiency scores whether a terminal is a transshipment/hybrid terminal or an import/export terminal.

BRA_01, which turns out to be efficient when the analysis is done with energy as input and output disaggregation into dry and reefer container (Model 4) but is far from efficient when output is aggregated and energy is omitted (Model 1, see Table 5). It is worth noting in this context, that BRA_01 has not been moved into a multidimensional space where it can only be a peer to itself but is still forming part of the frontier for ARG_01 and GEO_01 (see Appendix Tables 8 and 9). The fact that BRA_01 is efficient in Model 4 (Table 5) is arguably related to the fact that BRA_01 has a significantly higher share of reefer containers (28%) compared to the average terminal in the data set (8%).

Another terminal with a high share of reefer containers is COL_02, which also happens to be the terminal with the smallest overall container throughput. Moreover, while it had a different peer in the model with output disaggregation and energy input (Model 4), the efficiency score is still considerably low, whether under the assumption of variable return to scale as well as under the assumption of constant return to scale.

A further interesting case are Chilean (CHL) terminals, which partly are far from efficient in Model 1, but turn out to get an efficiency score of one in Model 4 (Table 5). As in the case of BRA_01, it can be noted that the Chilean terminals have not been moved into an area where they are only a peer to themselves but form part of the frontier for other terminals (see Appendix Tables 8 and 9). This is in particular interesting as the Chilean terminals move much higher shares of reefer containers, between 14% to 30% in comparison to the average terminal in the sample.

Table 5: DEA scores for model 1 to 4

Terminals	**Model 1: output aggregation no energy consumption as input**		**Model 2: output aggregation, energy consumption as input**		**Model 3: output disaggregation, no energy consumption as input**		**Model 4: output disaggregation, energy consumption as input**	
	CRS	**VRS**	**CRS**	**VRS**	**CRS**	**VRS**	**CRS**	**VRS**
ARG_01	0.363	0.471	0.425	0.557	0.41	0.556	0.455	0.671
ARG_02	0.276	0.294	0.289	0.327	0.297	0.308	0.316	0.338
BRA_01	0.492	0.555	0.594	0.663	1	1	1	1
BRA_02	0.318	0.362	0.426	0.463	0.321	0.372	0.426	0.474
BRA_03	0.241	0.311	0.328	0.376	0.254	0.322	0.341	0.383
BRH_01	0.438	0.484	0.492	0.501	0.46	0.485	0.503	0.505
BHS_01	0.956	1	1	1	1	1	1	1
CHL_01	0.71	0.822	0.714	0.829	1	1	1	1
CHL_02	0.446	0.446	1	1	1	1	1	1
CHL_03	0.87	0.888	0.87	0.888	1	1	1	1
COL_01	0.498	0.565	0.501	0.565	0.505	0.584	0.508	0.584
COL_02	0.158	0.158	0.174	0.228	0.383	0.383	0.383	0.383
COL_03	0.562	0.773	0.562	0.773	0.57	0.809	0.57	0.809
GEO_01	0.272	0.335	0.441	0.455	0.304	0.337	0.467	0.472
MEX_01	0.166	0.227	0.318	1	0.178	0.253	0.32	1
MEX_02	0.57	0.603	0.704	0.732	0.592	0.632	0.726	0.765
MEX_03	0.738	1	0.81	1	0.771	1	0.846	1
MOR_01	1	1	1	1	1	1	1	1
NIG_01	0.388	0.431	0.508	0.509	0.398	0.447	0.521	0.523
PAN_01	0.798	1	0.994	1	0.97	1	1	1
RUS_01	0.66	0.668	0.660	0.668	0.754	0.756	0.754	0.756
RUS_02	0.343	1	0.407	1	0.344	1	0.411	1
RUS_03	0.899	1	0.916	1	0.980	1	0.995	1
SWE_01	0.517	0.59	0.572	0.622	0.521	0.609	0.581	0.643
USA_01	1	1	1	1	1	1	1	1
VIE_01	0.908	1	1	1	0.915	1	1	1

Note: (ARG – Argentina, BHS - Bahamas, BRA – Brazil, BRH – Bahrain, CHL – Chile, COL – Colombia, GEO – Georgia, MEX – Mexico, MOR – Morocco, NIG – Nigeria, , PAN – Panama, RUS – Russia, SWE – Sweden, VIE – Vietnam).

Source: Authors

In fact, the terminal that only has itself as a peer and is not a peer to any other terminal in the model with energy and disaggregated output (model 4) is MEX_01 (Table 10). This, in turn, can be seen as an indication that output disaggregation and the inclusion of energy as an input leads to more advantageous comparisons, which reflects the differences in the multi-product nature of container terminals.

Peer-wise, when disaggregating output and considering energy as input (model 4), the container terminal from Latin America or the Caribbean are more often a peer to another terminal (see table 10). If this is compared to the reported peers in Table 7 (model 1), a clear difference can be noted. If the output is aggregated and energy is not considered as an input (model 1), most DMUs are benchmarked against highly specialized transhipment terminals (e.g. MOR_01 and PAN_01) independent of their geographic location as can be clearly seen when comparing tables 7 and 10 (Appendix).

One limitation of the comparisons above is that they do not provide any insight as to why certain changes might or might not have occurred. To address this matter the models 2 and 3 are compared with model 1 and 4 respectively. In Model 2 the energy variables are added but the output is aggregated (Table 5). In Model 3 output is disaggregated but no energy variables are added (Table 5).

When comparing the results between model 3 and 4, an initial finding is that the obtained efficiency scores between do not differ significantly (Table 5). However, that by itself does not provide much insight with regard to the frontier that has been modelled. Similar efficiency scores, being scalars after all, might be similar for a number of reasons. A comparison of the peers reported in Table 8 and 9 (Appendix) does provide insights as to whether a terminal is inefficient in relation to the same terminals as in the other model or if it is in fact benchmarked against other terminals.

From that perspective, COL_02 is interesting as it is benchmarked against CHL_02 regardless of the fact whether energy is considered as an input or not. Similar are the cases of COL_01, COL_03 and RUS_01 that are all benchmarked against the same peers regardless of the energy variables. The terminal MEX_02 gained more peers with the energy variables and ARG_01 and ARG_02 also maintained a very similar set of peers (cf.

Table 8 and Table 9). These findings indicate that the inclusion of energy variables contributes to additional insights (model 2), in comparison to using disaggregated output, but no energy variables (model 3).

The fact that the overall efficiency scores are similar in the different models and that the peers of the terminals did not change much can point towards one of two things: Either energy as an input does not add much to the model in general or the changes that are caused by adding energy as an input are similar to those caused by disaggregating output, meaning that energy consumption could also be accounted for by disaggregating output.

The obtained efficiency scores, again, appear to be rather similarly independent of whether energy is considered as an input or not. This must be understood against the background that, in this case, effects that energy might or might not have on the obtained efficiency score is not potentially captured by a disaggregated output as it could have been the case with the efficiency scores.

It is necessary to investigate, if the peers have changed to derive better insight regarding the question if energy matters in the context of efficiency analysis in container terminals. To do so, the reported peers in Table 7 are compared with those of Table 8.

The terminals CHL_03, COL_01, COL_03 and RUS_01 have the exact same peers regardless of whether energy is added as an input or not. The terminals ARG_01, ARG_02 and BRA_03 also still maintain almost the same peers when energy is added. Moreover, all of the following terminals BHS, CHL2, MEX3, MOR1, PAN1, RUS2, RUS3, USA1, VIE1 are potential peers in both models. It is not surprising both models have similar sets of peers. Most likely this does not mean more than these terminals are efficient regardless of whether the output is disaggregated or the model includes energy variables. This reinforces the idea that these variables are highly correlated and contain similar information, but at the same underlines the relevance of energy consumption and the output disaggregation when measuring efficiency.

Table 6 demonstrates the changes in inputs and outputs which might be necessary to make inefficient terminals full-efficient according to the VRS results of model 4. The results reveal significant inefficiencies in container terminal production. The sample terminals exhibit a mix of decreasing, increasing and constant returns to scale. Only one terminal exhibits constant returns to scale. The majority of terminals are operating at decreasing returns to scale, revealing that their size is too large regarding the activities performed. These terminals should reduce their operational scale to improve their level of efficiency. However, eight terminals show increasing returns to scale and given their small size of production need to enhance their efficiency by selecting a scaling up strategy.

In general several terminals could improve their efficiency by increasing its outputs or reduce its inputs (Table 6). For example, Given its current size, BRA_02 to be fully efficient could increase its dry and reefer output by 111% and 222% respectively. As for the inputs BRA_02 could decrease its crane capacity by 2%, labour by 18% and berth length by 23% respectively.

Table 6. Changes in outputs and inputs which are necessary to make inefficient terminals full-efficient according to Model 4

	Model 4				Potential improvement (%)						
	CRS	VRS	ES	Returns	Dry (output)	Reefer (output)	Electr-icity	diesel	STS crane equiv.	Labour	Berth length
ARG_01	0.455	0.671	0,679	irs	49	49	0	0	0	-5	0
ARG_02	0.316	0.338	0,936	drs	196	196	0	0	-27	0	-23
BRA_02	0.426	0.474	0,899	drs	111	222	0	0	-2	-18	-8
BRA_03	0.341	0.383	0,889	irs	161	908	-2	0	-2	-22	0
BRH_01	0.503	0.505	0,996	irs	98	98	-18	0	0	-45	-64
COL_01	0.508	0.584	0,87	drs	71	698	-23	-9	-30	0	0
COL_02	0.383	0.383	1	-	191	161	-90	-14	0	-28	-16
COL_03	0.57	0.809	0,705	drs	24	643	-37	-33	0	0	-20
GEO_01	0.467	0.472	0,989	irs	112	112	-4	0	0	-60	-77
MEX_01	0.32	1	0,32	irs	0	0	0	0	0	0	0
MEX_02	0.726	0.765	0,948	drs	31	285	0	0	0	-20	-1
MEX_03	0.846	1	0,846	irs	0	0	0	0	0	0	0
NIG_01	0.521	0.523	0,996	drs	91	260	0	-54	0	-41	-4
RUS_01	0.754	0.756	0,996	irs	32	32	-7	-26	-22	-2	0
RUS_02	0.411	1	0,411	irs	0	0	0	0	0	0	0
RUS_03	0.995	1	0,995	drs	0	0	0	0	0	0	0
SWE_01	0.581	0.643	0,902	drs	55	400	0	-6	0	0	-28

Source: Authors

5. Conclusion

DEA as other methods based on the frontier approach, allow to contrast the efficiency of an individual DMU relative to a set of other DMU that are homogenous. Following the initial research question, the output disaggregation in terms of reefer and dry containers did lead to efficiency scores substantially different from the ones obtained from a model considering container throughput in a generic aggregated way.

This confirms the assumption that the strategies of individual DMUs vary according to their containerized cargo mixes. The results reflect the different production processes, services and decision-making processes according to specific types of outputs.

Consequently, these findings are in particular relevant when analysing the efficiency of terminals with significant volumes of reefer traffic and comparing them to terminals with dry container only traffic. The relevance of reefer traffic varies across geographic regions. In this research, the differences are very apparent as the majority of the container terminals under study are located in the Latin American and Caribbean region, one of the main export regions of reefer cargo.

While theory suggests that a significant relationship exists between the volume of reefer container throughput and electricity consumption, said relationship could not be found in the obtained efficiency scores. This is not an argument against the relationship per se but rather an indication that other input variables that are highly linked to the volume of handled reefer containers contain similar information. Thus, a certain level of collinearity exists between the variables. One example for such relationship between inputs in the present research could be the one found between labour and energy consumption (i.e. electricity) inputs. Indeed, and in relation to the previous argument it might be that terminals with a greater share of reefer traffic require a greater number of workers, since reefer cargo requires a greater level of supervision than cargo in standard containers. This matter certainly deserves further research.

From a policy perspective the proposed output differentiation can be considered as highly relevant in scenarios where the environmental performance of terminals becomes a more relevant topic in the current efforts to lead ports and terminals towards sustainable performance. In general, full reefer containers have a higher carbon footprint than standard container due to their additional energy need for cooling of cargo, which is represented by a relative increase in electricity or diesel consumption in terminals with greater reefer cargo traffic. Thus, regulatory efforts regarding the performance and efficiency of terminals will benefit from a deeper understanding of a container terminal´s traffic mix. Since consumers are requiring more detailed information on the external effects caused by the supply chains of the products they purchase, a differentiation of energy consumption and thus emissions according to different cargo types will enable terminals to define and report their share in the overall supply chain external effects. In order to avoid a misleading comparisons between container terminals, the full variety of existing container terminal lay-outs, handling technologies and operating strategies should also be accounted for as detailed as possible.

Wang and Cullinane (2015) discuss the limitations of estimating efficiency limited to land, labour and equipment as key factors. They argue that numerous other factors can influence the way these factor endowments are interacting (e.g. operator model, level of vertical integration between shipping lines and terminal). Thus, this paper contributes to the consideration of a greater range of factors, and underscores the different needs and strategies in container terminals depending on the output formation.

Data availability still is a key challenge in port and container terminal analysis and this document is no exception to it. Firstly, it must be noted that certainly more recent data would have been desirable. Secondly, a more complex model and sounder statement could have been made if panel data were available.

In terms of variables, it would be desirable to construct future models with data that are more closely related to some of the economic objectives of a terminal. None of the variables used in this research are of monetary nature. In the case of output disaggregation, the difference in the price for handling one reefer container in comparison to a standard dry container might be of relevance. While the focus of this document was merely technical efficiency, the matter of economic efficiency is of significant interest for future investigation.

6. References

Acciaro, M., H. Ghiara, and M. Cusano. 2014. “Energy Management in Seaports: A New Role for Port Authorities.” *Energy Policy* 71: 4–12. doi:10.1016/j.enpol.2014.04.013.

Almawsheki, E. S., and M. Z. Shah. 2015. “Technical Efficiency Analysis of Container Terminals in the Middle Eastern Region.” *The Asian Journal of Shipping and Logistics* 31 (4): 477–486. doi:10.1016/j.ajsl.2016.01.006.

Azarkamand, S., G. Ferré, and R. M. Darbra. 2020. “Calculating the Carbon Footprint in Ports by Using a Standardized Tool.” *Science of the Total Environment* 734: 139407. doi:10.1016/j.scitotenv.2020.139407.

Bichou, K. 2011. “A Two-stage Supply Chain DEA Model for Measuring Container-terminal Efficiency.” *International Journal of Shipping and Transport Logistics* 3 (1): 6–26. doi:10.1504/IJSTL.2011.037817.

Bichou, K. 2013. “An Empirical Study of the Impacts of Operating and Market Conditions on Container-port Efficiency and Benchmarking.” *Research in Transportation Economics* 42 (1): 28–37. doi:10.1016/j. retrec.2012.11.009.

Budiyanto, M. A., T. Shinoda, F. A. Nugroho, and B. Wibowo. 2018. “Estimated of Energy Saving from the Application of Roof Shade on the Refrigerated Container Storage Yard.” *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 46 (1): 114–121.

Chandrasekhar Iyer, K., and V. P. S. Nihar Nanyamb. 2021. “Technical Efficiency Analysis of Container Terminals in India.” *The Asian Journal of Shipping and Logistics* 37 (1): 61–72. doi:10.1016/j.ajsl.2020.07.002.

Chang, V., and B. Tovar. 2014a. “Efficiency and Productivity Changes for Peruvian and Chilean Ports Terminals: A Parametric Distance Functions Approach.” *Transport Policy* 31: 83–94. doi:10.1016/j.tranpol.2013.11.007.

Chang, V., and B. Tovar. 2014b. “Drivers Explaining the Inefficiency of Peruvian and Chilean Ports Terminals.” *Transportation Research Part E* 67: 190–203. doi:10.1016/j.tre.2014.04.011.

Chang, V., and B. Tovar. 2017a. “Heterogeneity Unobserved and Efficiency: A Latent Class Model for West Coast of South Pacific Port Terminals.” *Journal of Transport Economics and Policy* 51 (2): 139–156.

Chang, V., and B. Tovar. 2017b. “Metafrontier Analysis on Efficiency and Productivity for West Coast of South Pacific Terminals.” *Transportation Research Part A: Policy and Practice* 103: 118–134.

Chang, V., and B. Tovar. 2021. "Efficiency Drivers for the South Pacific West Coast Port Terminals: A Two-stage Non-convex Meta Frontier DEA Approach." *Operational Research*. doi:10.1007/s12351-021-00626-5.

Charnes, A., W. W. Cooper, and E. Rhodes. 1978. "Measuring the Efficiency of Decision Making Units." *European Journal of Operational Research* 2 (6): 429–444. doi:10.1016/0377-2217(78)90138-8.

Cullinane, K., D. W. Song, P. A. Ji, and T. F. Wang. 2004. "An Application of DEA Windows Analysis to Container Port Production Efficiency." *Review of Network Economics* 3 (2): 1–23. doi:10.2202/1446-9022.1050.

Cullinane, K., D. W. A. Song, and T. Wang. 2005. "The Application of Mathematical Programming Approaches to Estimating Container Port Production Efficiency." *Journal of Productivity Analysis* 24 (1): 73–92. doi:10.1007/ s11123-005-3041-9.

Cullinane, K., T. F. Wang, D. W. Song, and P. Ji. 2006. "The Technical Efficiency of Container Ports: Comparing Data Envelopment Analysis and Stochastic Frontier Analysis." *Transportation Research Part A* 40 (4): 354–374.

Dias, J. C. Q., S. G. Azevedo, J. Ferreira, and S. F. Palma. 2012. "Seaport Performance Comparison Using Data Envelopment Analysis: The Case of Iberian Container Terminals." *International Journal of Business Performance Management* 13 (3/4): 426–449. doi:10.1504/IJBPM.2012.047304.

Dowd, T. J., and T. M. Leschine. 1990. "Container Terminal Productivity: A Perspective." *Maritime Policy & Management* 17 (2): 107–112. doi:10.1080/03088839000000060.

Drewry Shipping Consultant Limited 2018. "Perishable Reefer Trade Growth to Remain Strong." *[online]*, [accessed July 2021]. https://www.drewry.co.uk/news/news/perishable-reefer-trade-growth-to-remainstrong

Geerlings, H., and J. H. R. Van Duin. 2011. "A New Method for Assessing CO2-emissions from Container Terminals: A Promising Approach Applied in Rotterdam." *Journal of Cleaner Production* 19 (6–7): 657–666. doi:10.1016/j. jclepro.2010.10.012.

Gonzalez, M. M., and L. Trujillo. 2009. "Efficiency Measurement in the Port Industry: A Survey of the Empirical Evidence." *Journal of Transport Economics and Policy* 43 (2): 157–192.

Guerrero, C., and T. Rivera. 2009. *Mexico: Total Productivity Changes at the Principal Container Ports*. Review: ECLAC.Guimaraes, V. A., I. C. L. Junior, and P. A. A.

Garcia. 2014. “Environmental Performance of Brazilian Container Terminals: A Data Envelopment Analysis Approach.” *Social and Behavioral Sciences* 160: 178–187.

Hangga, P., and T. Shinoda. 2015. “Motion-Based Energy Analysis Methodology for Hybrid Straddle Carrier Towards Eco-Friendly Container Handling System.” *Journal of the Eastern Asia Society for Transportation Studies* 11: 2412–2431.

He, J., Y. Huang, and W. Yan. 2015. “Yard Crane Scheduling in a Container Terminal for the Trade-off between Efficiency and Energy Consumption.” *Advanced Engineering Informatics* 29 (1): 59–75. doi:10.1016/j. aei.2014.09.003.

He, J., Y. Huang, W. Yan, and S. Wang. 2017. “Integrated Internal Truck, Yard Crane and Quay Crane Scheduling in a Container Terminal considering Energy Consumption.” *Expert Systems with Applications* 42 (5): 2464–2487. 0957-4174.10.1016/j.eswa.2014.11.016.

Iris, C., and J. S. L. Lam. 2019. “A Review of Energy Efficiency in Ports: Operational Strategies, Technologies and Energy Management Systems.” *Renewable and Sustainable Energy Reviews* 112 (C): 170–182. doi:10.1016/j. rser.2019.04.069.

Itoh, H. 2002. “Efficiency Changes at Major Container Ports in Japan: A Window Application of Data Envelopment Analysis.” *Review of Urban & Regional Development Studies* 14 (2): 133–152. doi:10.1111/1467-940X.00052.

Kuo, K. C., W. M. Lu, and M. H. Le. 2020. ““Exploring the Performance and Competitiveness of Vietnam Port Industry Using DEA.” *The Asian Journal of Shipping and Logistics* 36 (3): 136–144. doi:10.1016/j.ajsl.2020.01.002.

Li, -L.-L., Y.-J. Seo, and M.-H. Ha. 2021. “The Efficiency of Major Container Terminals in China: Super-efficiency Data Envelopment Analysis Approach.” *Maritime Business Review* 6 (2): 173–187. doi:10.1108/MABR-08-2020- 0051.

Lim, S., H. Bae, and L. H. Lee. 2011. “A Study on the Selection of Benchmarking Paths in DEA.” *Expert Systems with Applications* 38 (6): 7665–7673. doi:10.1016/j.eswa.2010.12.148.

Lu, B., and X. Wang. 2012. “Application of DEA on the Measurement of Operating Efficiencies for East-Asia Major Container Terminals.” *Journal of Systems and Management Sciences* 2 (1): 1–18.

Martínez-Moya, J., B. Vazquez-Paja, and J. A. Gimenez Maldonado. 2019. “Energy Efficiency and CO2 Emissions of Port Container Terminal Equipment: Evidence from the Port of Valencia.” *Energy Policy* 131:312–319. 0301-4215. doi:10.1016/j.enpol.2019.04.044.

Mokhtar, K. 2013. “Technical Efficiency of Container Terminal Operations: A DEA Approach.” *Journal of Operations and Supply Chain Management* 6 (2): 1–19. doi:10.12660/joscmv6n2p1-19.

Munin, H. Z. 2020. “Does Higher Technical Efficiency Induce A Higher Service Level? A Paradox Association in the Context of Port Operations.” *The Asian Journal of Shipping and Logistics* 36 (4): 157–168. doi:10.1016/j. ajsl.2020.02.001.

Neufville, R. D., and K. Tsunokawa. 1981. “Productivity and Returns to Scale of Container Ports.” *Maritime Policy & Management* 8 (2): 121–129. doi:10.1080/03088838100000033.

Notteboom, T., C. Coeck, and J. van den Broeck. 2000. “Measuring and Explaining the Relative Efficiency of Container Terminals by Means of Bayesian Stochastic Frontier Models.” *International Journal of Maritime Economics* 2 (2): 83–106. doi:10.1057/ijme.2000.9.

Park, J., B. K. Lee, and J. M. W. Low. 2020. ““A Two-stage Parallel Network DEA Model for Analysing the Operational Capability of Container Terminals.” *Maritime Policy & Management* 1–22. doi:10.1080/ 03088839.2020.1859148.

Pérez-Reyes, R. A., and B. Tovar. 2009. “Measuring Efficiency and Productivity Change (PTF) in the Peruvian Electricity Distribution Companies after Reforms.” *Energy Policy* 37 (6): 2249–2261. doi:10.1016/j. enpol.2009.01.037.

Pjevčević, D., I. Vladisavljević, K. Vukadinović, and D. Teodorović. 2011. “Application of DEA to the Analysis of AGV Fleet Operations in a Port Container Terminal.” *Procedia-Social and Behavioral Sciences* 20: 816–825. doi:10.1016/j.sbspro.2011.08.090.

Rios, L. R., and A. C. G. Maçada. 2006. “Analysing the Relative Efficiency of Container Terminals of Mercosur Using DEA.” *Maritime Economics & Logistics* 8 (4): 331–346. doi:10.1057/palgrave.mel.9100168.

Roll, Y., and Y. Hayuth. 1993. “Port Performance Comparison Applying Data Envelopment Analysis (DEA).” *Maritime Policy & Management* 20 (2): 153–161. doi:10.1080/03088839300000025.

Sharma, M., and S. Yu. 2010. “Benchmark Optimization and Attribute Identification for Improvement of Container Terminals.” *European Journal of Operational Research* 201 (2): 568–580. doi:10.1016/j.ejor.2009.03.021.

Spengler, T., and G. Wilmsmeier. 2019. “Sustainable Performance and Benchmarking in Container Terminals—The Energy Dimension.” In *Green Ports: Inland and Seaside Sustainable Transportation Strategies*, edited by J. Monios and R. Bergqvist, 125–154, Elsevier.

Tongzon, J. 2001. “Efficiency Measurement of Selected Australian and Other International Ports Using Data Envelopment Analysis.” *Transportation Research Part A* 35: 113–128.

Tovar, B., and A. Wall. 2015. “Can Ports Increase Traffic while Reducing Inputs? Technical Efficiency of Spanish Port Authorities Using a Directional Distance Function Approach.” *Transportation. Research Part A* 71: 128–144.

Van Duin, J. H. R., H. Geerlings, A. Verbraeck, and T. Nafde. 2018. “Cooling Down: A Simulation Approach to Reduce Energy Peaks of Reefers at Terminals.” *Journal of Cleaner Production* 192: 72–86. doi:10.1016/j. jclepro.2018.04.258.

Wang, T., and K. Cullinane. 2015. “The Efficiency of European Container Terminals and Implications for Supply Chain Management.” In *Port Management. Palgrave Readers in Economics*, edited by H. E. Haralambides. London: Palgrave Macmillan. pp.253–272.

Wiegmans, B., and P. Witte. 2017. “Efficiency of Inland Waterway Container Terminals: Stochastic Frontier and Data Envelopment Analysis to Analyse the Capacity Design- and Throughput Efficiency.” *Transportation Research Part A: Policy and Practice* 106: 12–21.

Wilmsmeier, G. 2020. “Climate Change Adaptation and Mitigation in Ports.” *Maritime Transport and Regional Sustainability* 133–150. doi:10.1016/b978-0-12-819134-7.00008-3.

Wilmsmeier, G., J. Froese, A. Zotz, and A. Meyer. 2014. *Energy Consumption and Efficiency: Emerging Challenges from Reefer Trade in South American Container Terminals*. Chile: FAL Bulletin 329, ECLAC.

Wilmsmeier, G., and T. Spengler. 2016. *Energy Consumption and Container Terminal Efficiency*. Chile: FAL Bulletin 350, ECLAC.

Wilmsmeier, G., B. Tovar, and R. J. Sánchez. 2013. “The Evolution of Container Terminal Productivity and Efficiency under Changing Economic Environments.” *Research in Transportation Business & Management* 8: 50–66. doi:10.1016/j.rtbm.2013.07.003.

Woo, S.-H., S. J. Pettit, D.-W. Kwak, and A. K. C. Beresford. 2011. “Seaport Research: A Structured Literature Review on Methodological Issues since the 1980s.” *Transportation Research Part A* 45: 667–685.

Yang, Y.-C., and W.-M. Chang. 2013. “Impacts of Electric Rubber-tired Gantries on Green Port Performance.” *Research in Transportation Business & Management* 8: 67–76. doi:10.1016/j.rtbm.2013.04.002.

Yang, X., and T. L. Yip. 2019. “Sources of Efficiency Changes at Asian Container Ports.” *Maritime Business Review* 4 (1): 71–93. doi:10.1108/MABR-10-2018-0043.

Yip, T. L., X. Y. Sun, and J. J. Liu. 2011. “Group and Individual Heterogeneity in a Stochastic Frontier Model: Container Terminal Operators.” *European Journal of Operational Research* 213 (3): 517–525. doi:10.1016/j. ejor.2011.03.040.

7. Appendix

Table 7: DMUs with their peers under VRS assumption – Model 1

DMU	**Peers**			
ARG_01	USA_01	MOR_01	MEX_03	RUS_02
ARG_02	BHS_01	MOR_01		
BRA_01	MOR_01	USA_01	RUS_02	
BRA_02	PAN_01	MOR_01		
BRA_03	USA_01	MOR_01	MEX_03	RUS_02
BRH_01	MOR_01	USA_01		
BHS_01	BHS_01			
CHL_01	RUS_03	BHS_01	USA_01	
CHL_02	USA_01			
CHL_03	MOR_01	USA_01		
COL_01	BHS_01	RUS_03	USA_01	
COL_02	USA_01			
COL_03	MOR_01	RUS_03	USA_01	
GEO_01	USA_01	MOR_01		
MEX_01	USA_01	MOR_01	MEX_03	RUS_02
MEX_02	MOR_01	PAN_01		
MEX_03	MEX_03			
MOR_01	MOR_01			
NIG_01	PAN_01	MOR_01		
PAN_01	PAN_01			
RUS_01	MOR_01	MEX_03		
RUS_02	RUS_02			
RUS_03	RUS_03			
SWE_01	MOR_01	RUS_03	USA_01	
USA_01	USA_01			
VIE_01	VIE_01			

Note: (ARG – Argentina, BHS - Bahamas, BRA – Brazil, BRH – Bahrain, CHL – Chile, COL – Colombia, GEO - Georgia, MEX – Mexico, MOR – Morocco, NIG – Nigeria, PAN – Panama, RUS – Russia, SWE – Sweden, VIE – Vietnam).

Source: Authors

Table 8: DMUs with their peers under VRS assumption – Model 2

DMU	Peers			
ARG_01	VIE_01	USA_01	RUS_02	CHL_02
ARG_02	VIE_01	RUS_03	BHS_01	MOR_01
BRA_01	MOR_01	VIE_01	RUS_02	
BRA_02	VIE_01	BHS_01	PAN_01	
BRA_03	VIE_01	RUS_02	MOR_01	MEX_03
BRH_01	VIE_01	USA_01	MOR_01	
BHS_01	BHS_01			
CHL_01	VIE_01	BHS_01	RUS_03	USA_01
CHL_02	CHL_02			
CHL_03	USA_01	MOR_01		
COL_01	RUS_03	BHS_01	USA_01	
COL_02	USA_01	CHL_02		
COL_03	MOR_01	RUS_03	USA_01	
GEO_01	PAN_01	MOR_01	VIE_01	
MEX_01	MEX_01			
MEX_02	PAN_01	BHS_01	MOR_01	VIE_01
MEX_03	MEX_03			
MOR_01	MOR_01			
NIG_01	BHS_01	USA_01	MOR_01	
PAN_01	PAN_01			
RUS_01	MOR_01	MEX_03		
RUS_02	RUS_02			
RUS_03	RUS_03			
SWE_01	BHS_01	USA_01	RUS_03	VIE_01
USA_01	USA_01			
VIE_01	VIE_01			

Note: (ARG – Argentina, BHS - Bahamas, BRA – Brazil, BRH – Bahrain, CHL – Chile, COL – Colombia, GEO - Georgia, MEX – Mexico, MOR – Morocco, NIG – Nigeria, PAN – Panama, RUS – Russia, SWE – Sweden, VIE – Vietnam

Source: Authors

Table 9: DMUs with their peers under VRS assumption – Model 3.

DMU	Peers				
ARG_01	USA_01	CHL_03	BRA_01	MOR_01	RUS_02
ARG_02	CHL_01	BHS_01	PAN_01	MOR_01	
BRA_01	BRA_01				
BRA_02	PAN_01	MOR_01			
BRA_03	USA_01	MOR_01	MEX_03	RUS_02	
BRH_01	MOR_01	CHL_03	USA_01		
BHS_01	BHS_01				
CHL_01	CHL_01				
CHL_02	CHL_02				
CHL_03	CHL_03				
COL_01	BHS_01	RUS_03	USA_01		
COL_02	CHL_02				
COL_03	MOR_01	RUS_03	USA_01		
GEO_01	USA_01	MOR_01	CHL_03		
MEX_01	USA_01	CHL_03	BRA_01	MOR_01	RUS_02
MEX_02	MOR_01	PAN_01			
MEX_03	MEX_03				
MOR_01	MOR_01				
NIG_01	PAN_01	MOR_01			
PAN_01	PAN_01				
RUS_01	RUS_02	CHL_03	MOR_01		
RUS_02	RUS_02				
RUS_03	RUS_03				
SWE_01	MOR_01	RUS_03	USA_01		
USA_01	USA_01				
VIE_01	VIE_01				

Note: (ARG – Argentina, BHS - Bahamas, BRA – Brazil, BRH – Bahrain, CHL – Chile, COL – Colombia, GEO - Georgia, MEX – Mexico, MOR – Morocco, NIG – Nigeria, PAN – Panama, RUS – Russia, SWE – Sweden, VIE – Vietnam).

Source: Authors

Table 10: DMUs with their peers under VRS assumption – Model 4

DMU	Peers					
ARG_01	USA_01	MOR_01	RUS_02	CHL_02	VIE_01	BRA_01
ARG_02	BHS_01	CHL_02	MOR_01	VIE_01	CHL_01	
BRA_01	BRA_01					
BRA_02	VIE_01	BHS_01	PAN_01			
BRA_03	VIE_01	RUS_02	MEX_03			
BRH_01	USA_01	VIE_01	MOR_01	CHL_02		
BHS_01	BHS_01					
CHL_01	CHL_01					
CHL_02	CHL_02					
CHL_03	CHL_03					
COL_01	BHS_01	RUS_03	USA_01			
COL_02	CHL_02					
COL_03	MOR_01	RUS_03	USA_01			
GEO_01	PAN_01	MOR_01	BRA_01	VIE_01		
MEX_01	MEX_01					
MEX_02	MOR_01	BHS_01	PAN_01	VIE_01		
MEX_03	MEX_03					
MOR_01	MOR_01					
NIG_01	BHS_01	MOR_01	USA_01			
PAN_01	PAN_01					
RUS_01	MOR_01	CHL_03	RUS_02			
RUS_02	RUS_02					
RUS_03	RUS_03					
SWE_01	USA_01	RUS_03	BHS_01	VIE_01		
USA_01	USA_01					
VIE_01	VIE_01					

Note: (ARG – Argentina, BHS - Bahamas, BRA – Brazil, BRH – Bahrain, CHL – Chile, COL – Colombia, GEO – Georgia, MEX – Mexico, MOR – Morocco, NIG – Nigeria, PAN – Panama, RUS – Russia, SWE – Sweden, VIE – Vietnam).

Source: Authors

Chapter 2: Potential of cold-ironing for the reduction of externalities from in-port shipping emissions: The state-owned Spanish port system case

1. Introduction

Vessels account for 90% of international transport and for 2.2% of worldwide emissions (Smith et al., 2015). Apart from the often referred to CO_2 emissions, vessels also contribute in a significant way to emissions of NO_x, SO_x and particulate matter. It is therefore not surprising that considerable mitigation efforts are undertaken by stakeholders from, both, the private as well as public sector to mitigate and abate these emissions. In particular, emissions of short-lived climate pollutants (SLCPs) are of interest when considering vessels calling at ports that are in or near to densely populated areas. SLCPs, such as for example particulate matter, stay in the atmosphere for a relatively short time period when compared to CO_2. The negative health impacts might however be much greater for the people in the direct vicinity of where the emission occurs.

During the past decades, different approaches can be observed to avoid or mitigate emissions and the associated external costs that are caused by shipping. In particular, in ports that are in the direct vicinity of densely populated areas. One of the approaches to reduce said emissions from vessels in ports, cold ironing, is often perceived (Cullinane and Cullinane, 2019; Pettit et al., 2018) as one way to a cleaner and more environmentally friendly sea transport.

The issue of allocating the limited resources amongst the various options to attain sustainability and emission reduction goals is a common challenge for many ports. Analysis of subsidy programs for cold ironing as a potential strategy have been carried out (Wu and Wang, 2020) and even though cold ironing has a relatively high marginal cost when considered as a mere CO_2 abatement technology (Wan et al., 2018), it is shown in this paper, that the benefits of cold ironing are substantial when considered as a way of reducing the external cost to the society in general and to the port cities in particular.

However, to be able to assess the benefits that would come from cold ironing, it is necessary to have a deeper look into how the introduction of the measure would impact the different ports. The results obtained in this paper provide a wide insight into the potential that cold ironing could have for the Spanish ports and they allow to take a more granular decision about the question of investment in cold ironing.

In addition, policy makers face the challenging task of implementing rules and regulations that encourage the port sector to reduce their environmental impact. One possible way to contribute to a more sustainable port sector is to internalize external costs. A challenge for internalizing external costs is the fact that external costs are very often not known. In the event of some metrics were known, they would be hardly comparable (Tichavska and Tovar, 2015b). The findings in this report make it possible to measure the cost of not having cold ironing in various ports and can help the policy makers conceive rules and regulations that are likely to yield the highest benefit for the society. Also, by comparing eco-efficiency indicators, policy makers could be aware of potential risks that certain regulations could have in terms of wrong incentives when considering only overall external costs. By way of example, if a policy-maker introduces a regulation only addressing overall external costs, it would entirely disregard the question of how many vessels are calling a port and how long the vessels are staying in the port. However, by comparing eco-efficiency indicators, policy makers would be made aware of potential risks that certain regulations could have in terms of wrong incentives if there are great discrepancies between ship calls and port stay durations.

Furthermore, market-based approaches such as emissions trading are often mentioned (cf. Kachi et al., 2019) as a way to promote more sustainable alternatives to the use of fossil fuels such as cold ironing. The advantage of mark-based approaches is, that they could offset the high initial cost of the installation of cold ironing facilities on the shore side (Dai et al., 2019). Yet, in order to implement a market-based approach, such as emission trading between ports, it is necessary to have a well-established and understood basis. The findings in this report could serve as a base for the policy makers and the stakeholders from the port sector that could have an insight into how the installation of shore-power supply facilities could financially benefit the respective port (e.g. through the emission trading).

Apart from these contributions to the practical side of policy implications and further benefits for other stakeholders, this work also contributes in a significant way to the existing body of literature. It offers, to the best of the knowledge of the authors, for the first time a nation-wide overview of the external costs that can be allocated to berthed vessels in all major ports of a country highlighting where investments can be undertaken to get the maximum reduction on these external costs in its port-cities.

Moreover, this paper, offers for the first time insights into the potential of cold-ironing for the State-owned Spanish Port System case by providing an estimation that allows for comparisons and also highlights the Spanish ports[4] that can be of interest for further research due to their higher potential. On the other hand, these measurements (external costs) are also useful to estimate ports' environmental efficiency providing important information for policymakers (Tovar and Wall, 2019b, 2020a).

This work is structured as follows: First, a review of relevant literature with regard to emissions from vessels in the vicinity of ports in general and cold ironing in particular is given. This is followed by a brief overview of the area under study, Spain, and its port system. The methodology is described in Section 4. The results are provided in Section 5. Section 6 concludes.

2. Literature

The movement towards cleaner shipping is reflected by the amount of literature that has been published in this field of research since 2006 (Davarzani et al., 2016). The matter of emissions from ships in the vicinity of a port has already received a noticeable amount of attention. One frequently cited paper in this respect is the one of Merk (2014) who reported, based on a literature review, that the share of shipping emissions in total emissions in port cities with regard to some pollutants such as SO_2 can be as high as 54%. Following the Benefits Table database (BETA), he estimated the external costs of the 50 largest ports to be 12 billion Euro per year. Cold ironing as an abatement measure is also mentioned in particular. It is sometimes understood as a measure that can best unveil its true potential

---

[4] A deeper analysis of each one of those ports has been left as a task for future research. This tailored analysis is needed because differences in the contribution to total external costs from different ship categories exist between ports and they should be considered when it comes to deciding how to prioritize the investment (e.g. which berths, and therefore ship categories, the OPS will be offered first to).

when the initial costs are offset and hence, the economic performance is improved through measures such as emission trading (Dai et al., 2019).

For the case of the port of Piraeus in Greece, Chatzinikolaou et al. (2015) estimated the total external health cost, to be approximately 25.3 million Euro,of which more than half (61%) was attributed to particulate matter. Maragkogianni and Papaefthimiou (2015) considered 4 ports, including Piraeus and only focused on cruise ship activity. For the port of Piraeus, they reported that the external costs are 11.8 million Euro or 7.88 million Euro according to the New Energy Externalities Development for Sustainability (NEEDS) and Clean Air for Europe (CAFE) methodologies, respectively.

In relation to cold ironing, it is also recognized (Zis et al., 2014) that the type of vessel plays an important role as this can be determining for the time spend at berth which in turn can be a deciding factor for whether to use cold ironing or not.

Innes and Monios (2018) mention 28 ports with cold ironing facilities and Zis (2019) mentions 43 ports with either cold ironing already installed or planned. In this context, it is worth noting that said cold ironing facilities are not universally made available to all vessels. In most cases, the option of receiving a shore power connection is only available for a certain type of vessel (e.g. Ro-Ro or cruise ships) and also only at certain berths.

This is related to the technical challenges of installing cold ironing facilities in ports as described by Sciberras et al. (2015). A first and often mentioned challenge is that the alternating current on vessels very often has a frequency of 60 Hz while national power grids in Europe generally operate at 50 Hz. This makes it right from the beginning more challenging for European ports to implement the said technology as compared to ports in the United States where the frequency of alternating current in the national power grid is in fact 60 Hz.

Ballini and Bozzo (2015) undertook a case study for a new cruise pier in the port of Copenhagen which is “prepared for the introduction of cold-ironing”. The study worked on the assumption that about 60% of the cruise ships operating in the Baltic Sea could be retrofitted with cold ironing equipment, and an approximation that the overall cost of final installation would amount to a capital cost of 37 million Euro. In a cost benefit analysis based on these assumptions, the result was that the capital cost could be recovered, merely by health cost savings and disregarding CO_2 emissions, after 12–13 years. Innes and Monios (2018) found in a similar case study with regard to the port of Aberdeen, in Scotland, that in the most optimistic scenario, the capital as well as operating cost could be recovered in only 7 years. Reason for this considerably lower estimate are due to a generally rather clean and increasingly clean energy mix in Scotland, the assumption that all vessels would be using cold ironing and an assumed much lower initial investment cost for installation. In a worst-case scenario, Innes and Monios (2018) estimated the payback period to be almost 14 years. The estimates should however be taken with a grain of salt as no sensitivity analysis was carried out with regard to the discount rate.

The matter of how the electric energy is produced is not only a key factor in cost benefit analysis but also in general when considering cold ironing. While local effects would certainly be shifted to the location where the energy is produced, the matter of global effects still persist. Zis (2019) reports that an auxiliary engine, powered by marine gas oil, would emit between 678 and 709 g of CO_2 per KWh whereas 940 g of CO_2 per kWh would be emitted by a coal power plant. While the population density tends to be comparably low in regions of coal power plants and a smaller proportion of the population would be affected by the negative local effects of energy production with a coal power plant, the negative global effect caused by CO_2 would be less if the electricity needed by a given vessel would be produced by means of auxiliary generator. Still, Zis (2019) also reports on the emission factors for grid electricity for ports around the world and all of them are way below the above-mentioned 678–709 g/kWh for the marine gas oil engine.

This matter can be particularly relevant in the case of Spain, which has considerable number of ports on small islands and concrete plans for the cold ironing in the near future (“Main Spanish Shipping Liners”, 2018). The electric power grid of islands is often not connected to the mainland and all electricity production has to take place right on the island in question. Accordingly, the emissions per kilowatt hour can differ significantly from the overall emissions per kilo watt hour of the respective country. For the case of Gran Canaria, Tichavska and Tovar (2015a) argued that, even though the island is currently heavily dependent on the use of oil for electricity production, the regional government of the Canary Islands has already taken steps to support the use of renewable energy. In this context, it should be noted that there are also efficiencies of scale when it comes to electricity production from oil. This implies that even electricity production from oil can be assumed to emit less CO_2 per KWh than electricity production from oil onboard a given vessel.

Another relevant factor taken up by Zis (2019) is the one of economic viability of cold ironing for ship operators. This question is heavily intertwined with the volatility of energy prices and with the question of where a given vessel is bunkering as bunker prices tend to differ substantially between different locations. Zis (2019) reports the costs for producing electricity by means of auxiliary engines and the costs of buying electricity from the national power grid for the years from 2010 to 2017 for several countries. Due to the plummeting oil prices between 2014 and 2016, the production of electricity by means of auxiliary engines would have been cheaper when compared to most countries. However, already between the years of 2016 and 2017 an increase in oil prices could be observed while prices for electricity from the national power grids maintained relatively stable. It should also be noted that electricity taken from shore is taxed in some regions whereas electricity produced by means of auxiliary engines usually is not subject to said taxes (Kumar et al., 2019). This is currently a matter of debate within the European Union in general and in Spain in particular. The European Parliament (2018) has recognized the importance of the taxation scheme for shore-side power supply and called therefore on their Member States to review the disparities in energy taxation in a resolution. The Spanish Institute for the Diversification and Saving of Energy has announced that new electricity regulations will come into force with regard to ships at berth ("IDAE announces", 2018). Germany and Sweden were already allowed by the European Union to provide electricity by means of cold ironing at a reduced tax rate in 2011 (Ballini and Bozzo, 2015).

Notwithstanding the above-mentioned challenges for the implementation of cold ironing, there are good reasons to believe that a higher penetration of this technology will be observable in the upcoming years. One of the reasons is that ports could be considering making the use of cold ironing compulsory. The latter has to be understood against the background that some argue that "the main barrier for the further implementation of [cold ironing] solutions […] is the associated high installation cost" (Zis, 2019).

In addition, given the current regulations within sulphur emission control areas (SECAs), the operators of vessels are met with a range of different sulphur limits of marine fuel. Inside EU SECAs (European Maritime Safety Agency, 2016; European Parliament and Council, 2016.) the sulphur limit is currently 0.1%. While outside of SECAs the maximum sulphur limit has been 3.5% until 2020 when the Sulphur limit became 0.5% instead of 3.5%. However, the sulphur limit is 0.1% at berth/anchor even outside EU SECAs if the vessel in question is more than 2 h at berth or at anchor. For a passenger vessel that half of the year is sailing in the Mediterranean and Baltic Sea and the other half of the year is sailing in the area of Latin America, this might mean that fuel with two different types of sulphur content might need to be stored on board of the vessel to always be able to use the cheapest permissible fuel. This, of course, is impractical for several reasons.

One possible way to address said challenge is the installation of scrubber systems or a cold ironing system on board. The cost of retro fitting a scrubber system is reported to be up to 6 million USD (Zis et al., 2016) whereas the cost of installing cold ironing equipment is comparably cheaper, with a cost of between 300.000 and 2 million USD. This would also have the additional benefit of not being forced to use the most expensive fuel with 0.1% sulphur content at berth.

The key benefit of cold ironing technology, however, lies in the reduction of local and global emissions and noise reduction. Depending on the region, the effects naturally seem to differ. For six container terminals in different regions of the world Zis et al. (2014) report that by means of cold ironing a reduction potential for "CO_2, SO_2, NO_x and BC emissions by 48-70 per cent, 3–60 per cent, 40–60 per cent and 57–70 per cent, respectively" exists. In Gothenburg, Sweden, an actual reduction of 10% of CO_2 emissions from RoRo and ferry ships was reported (Styhre et al., 2017). Also, Styhre et al. (2017) report that the main part of the emissions occurs during the "at berth" mode of operation and are consistent with Zis et al. (2014), arguing that a greater saving potential exists for larger vessels. In absolute numbers Styhre et al. (2017), has calculated the emissions to be 150.000, 240.000, 97.000 and 95.000 tonnes of CO_2 emissions for the ports of Gothenburg, Long Beach, Osaka and Sydney respectively. A hypothetical estimation if all ships were to use cold ironing is provided by Chang and Wang (2012) for the Kaohsiung harbour in Taiwan, estimating a potential reduction of CO_2 emissions by 57.2%, NO_x emissions by 49.2%, SO_x by 63.2%

and PM emissions by 39.4%. Adamo et al. (2014) found that by cold ironing in the port of Taranto, Italy, emissions of NO_x and CO_2 could be reduced by 1.097 tons per year and 25.686 tons per year respectively.

Even though a significant amount of research has been carried out, a certain gap in literature still can be identified: Spain was never subject to a case study where virtually all ports could be compared. The benefit of doing so lies in the fact that the so values obtained allow for a more in depth understanding of externalities in the context of ports and the potential of cold ironing on a country wide basis.

The matter of credibility in relation to external cost estimates is commonly raised and also underlined by the conducted review of relevant literature. Until now, no entirely comparable set of external cost estimates is made available. This matter is to some extent addressed by the here presented research as a large number of ports is analysed by means of the same methodology.

3. Case context – The Spanish port system

The network of Spanish ports moves goods worth 200.000 million Euro or 20% of the country's GDP each year. That underlines the strategic importance of ports that handle 57% of consumer goods exports and 78% of imports from and to Spain.

By the end of 2016, Spanish ports reached a new historical high in throughput. Total goods traffic in 2016 was 495.58 million tons. The largest type of traffic was containerized general cargo (33.97%), followed closely by liquid bulk (33.81%), solid bulk (18.56%) and break bulk (13.65%). Moreover, more than 31 million passengers, 27.95% of which were cruise passengers and 76.53% were non-cruise passengers, utilised Spanish ports. The ports with the highest throughput are the ones of Algeciras, Valencia and Barcelona. On national level, the five ports with the highest gross traffic growth in 2015 were the ports of Algeciras, Huelva, Valencia, Baleares and Barcelona.

Spain plays a major role in the European port sector. Rodríguez-Alvarez and Tovar (2012) and more recently Tovar and Wall (2020b) have analysed the Spanish regulatory framework of the port sector and found that it has undergone substantial changes during the last three decades. The port authorities follow the landlord model. Currently, they have great autonomy with regard to legal, managerial as well as budget aspects of their work. The said port authorities are governed by the state-owned Enterprise of National Ports (Ente Público Puertos del Estado, EPPE). Fig. 1 depicts the forty-six General Interest ports.[5]

Source: EPPE, 2019

Fig. 1. Spanish general interest ports, source: EPPE, 2019.

General Interest ports are managed by port authorities that are governed by the EPPE. In this context, it should be noted that a variety of different ports fall under said regime. Spanish ports are relatively heterogeneous in terms of specialisation and size. Some ports handle cargo and passenger traffic whereas the main activity of others is cargo (passenger

---

[5] Following Tovar and Wall (2020a, b) "Ports in Spain can be classified into two legal categories. General interest ports are the property of the State (dependent on the Ministry of Public Works) and must comply with certain characteristics. These may include, among others, international maritime activity, provision of services of strategic national economic importance or port activity that affects several Autonomous Communities (regions)."

traffic is virtually non-existent). In addition, within one port, several different terminals can operate that handle different cargos or even passengers.

Table 1 shows the top ten Spanish ports by type of cargo and passengers. A first observation with regard to the cargo as well as passenger throughput is that there are some ports in the system that are amongst the most important ports in more than one category. One of the ports is Algeciras, which happens to be the most important port for containerized cargo, liquid bulk cargo as well as for non-cruise passengers in Spain. Moreover, Algeciras is the third most important Spanish general cargo port. Other ports seem to make use of the apparent economies of scope as well. Castellon, located north of Valencia at the east coast of Spain, is Spain-wide the port with the sixth highest container as well as solid bulk throughput. In terms of liquid bulk, it ranks seventh. Bilbao comes in fifth with regard to its general cargo, liquid bulk and container throughput. In terms of solid bulk, it comes in eighth. This pattern continues and it can be argued that many ports that have specialised in one cargo also have specialised in another cargo.[6]

In Spain, passenger traffic by sea has been of high importance in certain geographic regions, such as the Strait of Gibraltar, the Canary Islands and the Balearic Islands. A distinction is made between cruise passengers and non-cruise passengers based on the vessel and its destinations. Passengers that are embarking on a short-distance voyage with a passenger or vehicle ferry are considered non-cruise passengers.

Moreover, cruise shipping and the associated cruise passengers are of significant importance in Spain as it has not stopped growing since its appearance more than two decades ago. However, it should be noted that there are seasonal differences between the regions due to their different climatic conditions. While the most important Spanish cruise destinations in the Mediterranean Area, such as Barcelona and Palma, are chiefly frequented between May and October, the destinations on the Canary Islands receive a substantial amount of their cruise passengers during the winter of the northern hemisphere due to the warm climate even during those months.

---

[6] For a deeper analysis of this issue, see Tovar and Wall (2017, 2019).

In absolute numbers, Barcelona with more than 2.5 million passengers stands out as the most important cruise port in Europe and ranking fifth on a worldwide level. The Palma port (Balearic Islands) with almost 2 million passengers rank fourth in Europe and thirteenth in the world. On the north-western Atlantic coast of Spain, more than 465.000 passengers were counted, representing 5.4% of the national total. Of that, 200.000 passengers could be allocated to the port of Vigo. Two million cruise passengers were counted in the Canary Islands in 2015, making it the third most active market in Europe and arguable the most active market in Europe during the European winter. On the Canary Islands, Tenerife and Las Palmas are the most important ports with 559.100 and 615.485 cruise passengers, respectively. It is worth noting that the electricity consumption of passenger vessels in hoteling is considerably higher than the one of cargo vessels. Therewith comes the greatest potential for the reduction of externalities by means of cold ironing for those vessels.

Table 1
Top Ten Spanish ports by type of cargo and passengers.

Liquid bulk		Solid bulk		Container	
Port	Ton	Port	Ton	Port	TEUs
Algeciras	27,309,859	Gijón	16,023,647	Algeciras	4,761,444
Cartagena	25,025,669	Tarragona	9,065,474	Valencia	4,670,810
Huelva	24,136,062	Huelva	5,759,383	Barcelona	2,236,961
Tarragona	20,268,771	Cartagena	5,304,817	Las Palmas	851,473
Bilbao	18,087,202	San Cibrao	5,230,449	Bilbao	596,689
Barcelona	11,415,816	Castellón	5,198,982	Castellón	226,903
Castellón	8,354,528	Barcelona	4,430,798	S/C Tenerife	350,337
A Coruña	8,169,622	Bilbao	4,362,064	Vigo	218,044
S/C Tenerife	6,012,950	A Coruña	4,345,101	Alicante	159,664
Las Palmas	4,411,677	Ferrol	4,175,590	Sevilla	145,672
Non containerized general cargo		**Cruise Passenger**		**Non cruise passenger**	
Port	Ton	Port	Number	Port	Number
Barcelona	10,737,040	Barcelona	2,683,594	Algeciras	4,220,710
Valencia	8,114,037	Palma	1,631,206	Ibiza	2,461,249
Algeciras	7,591,875	Las Palmas	615,485	La Sabina	2,074,374
Palma	7,039,505	S/C Tenerife	559,100	Ceuta	1,923,483
Bilbao	3,126,518	Málaga	444,176	Los Cristianos	1,535,538
Las Palmas	3,053,536	Valencia	403,264	Tarifa	1,397,338
S/C Tenerife	2,345,678	Cadiz	385,067	S/C Tenerife	1,319,165
Sagunto	2,329,058	Arrecife	377,803	Barcelona	1,275,366
Ibiza	2,310,508	Ibiza	251,249	SS de la Gomera	1,228,332
Pasajes	2,216,792	S/C de la Palma	224,448	Las Palmas	1,108,666

Source: Own elaboration based in EPPE Annual Report

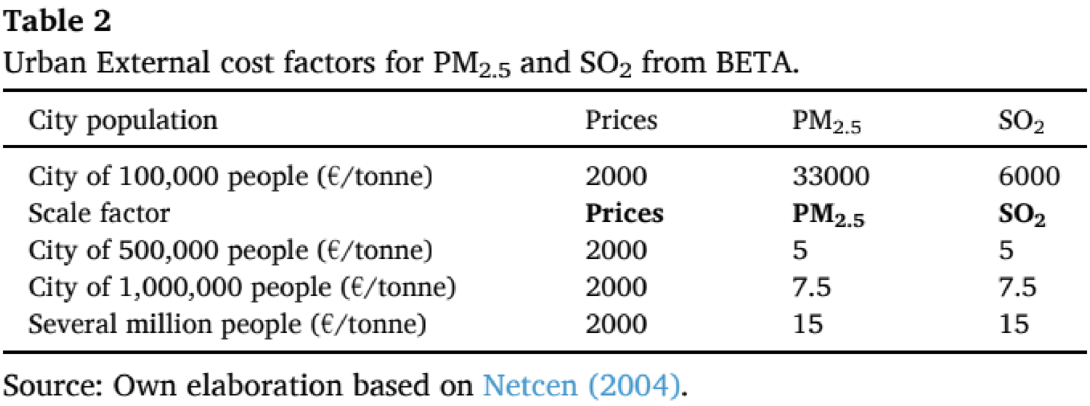


Table 2

Urban External cost factors for $PM_{2.5}$ and SO_2 from BETA.

City population	Prices	$PM_{2.5}$	SO_2
City of 100,000 people (€/tonne)	2000	33000	6000
Scale factor	**Prices**	**$PM_{2.5}$**	**SO_2**
City of 500,000 people (€/tonne)	2000	5	5
City of 1,000,000 people (€/tonne)	2000	7.5	7.5
Several million people (€/tonne)	2000	15	15

Source: Own elaboration based on Netcen (2004).

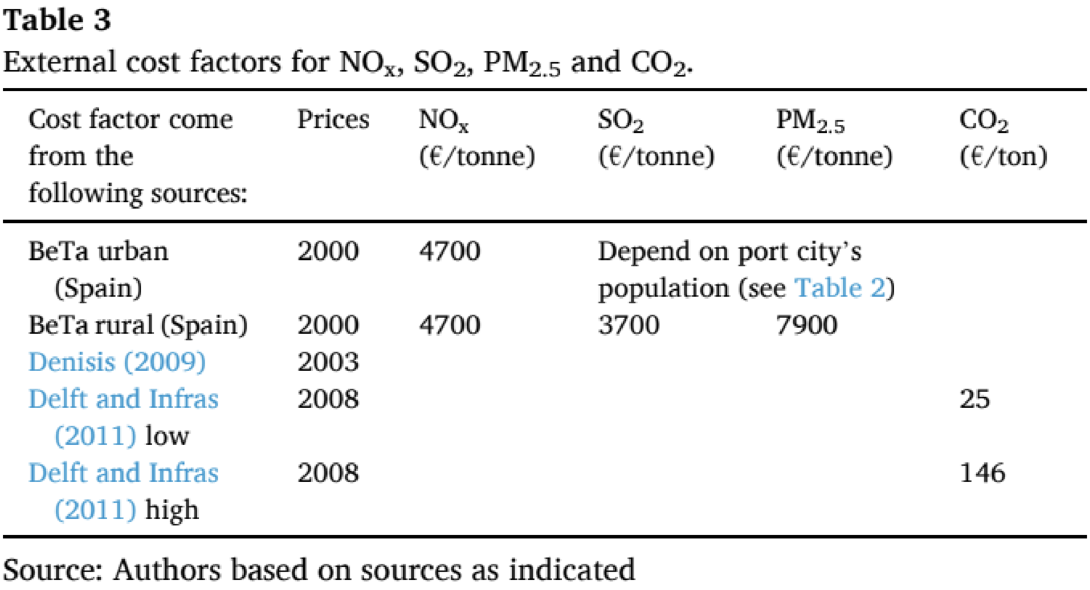


Table 3

External cost factors for NO_x, SO_2, $PM_{2.5}$ and CO_2.

Cost factor come from the following sources:	Prices	NO_x (€/tonne)	SO_2 (€/tonne)	$PM_{2.5}$ (€/tonne)	CO_2 (€/ton)
BeTa urban (Spain)	2000	4700	Depend on port city's population (see Table 2)		
BeTa rural (Spain)	2000	4700	3700	7900	
Denisis (2009)	2003				
Delft and Infras (2011) low	2008				25
Delft and Infras (2011) high	2008				146

Source: Authors based on sources as indicated

4. Methodology

With the introduction of a variety of plans and programs to mitigate or, at least, reduce emissions from vessels, ports have started to move to a more environmentally friendly way of handling cargo and passengers. In the case of Spain, a major initiative is the OPS Master Plan. this plan is, in turn, part of the National Action Framework for the development of infrastructure for the use of alternative fuels in the transport sector. This, again, is in compliance with Article 13 of Directive 2014/94 EU.

Estimating the potential benefits to society that the supply of vessels with on shore electricity could have is a crucial step for the OPS Master Plan project as well as the Spanish National Ports Agency, which in turn is responsible for the coordination of said plan. A prerequisite for doing so is to first estimate the emissions of CO_2 and other pollutants such as NO_x, SO_x, and PM from berthed ships in the Spanish port system.

The emission released by vessels while hoteling operation inside one of the Spanish ports during 2016[7] has been calculated as part of the EU funded research project Master Plan for OPS in Spanish Ports (Agreement No. INEA/CEF/TRAN/M2015/1128893). To do that, data regarding the time a vessel is berthed, the size of the vessel and the type of the vessel are needed. The type of the vessel is needed to make estimations with regard to the auxiliary engine power. Based on this data, it is then possible to compute the emissions with Equation (1):

$$E_i = AE \cdot t \cdot FE_i \ (1)$$

Where E are the emissions in tons for pollutant i, AE is the auxiliary engine power in kilowatt. The power is estimated using the bin responding to vessel in question, following the 3rd International Maritime Organization (IMO) Study on Greenhouse gases (GHG) (Smith et al., 2015) The time, t, is calculated in hours and FE is the emission factor for pollutant i in tons per kilowatt-hour.

The proposed methodology of the European Environment Agency (EEA) and the US Environmental Protection Agency (EPA) in the years 2013 and 2010 respectively was followed based on the following three assumptions: (1) Tier II is achieved by the auxiliary engines with respect to NO_x, (2) the auxiliary engines are of "medium speed diesel" type and (3) the auxiliary engines are burning Marine Diesel Oil (MDO)/Marine Gasoil (MGO) fuel. For the other data it was referred to operational and vessel traffic information such as Automatic Identification System (AIS) data, port call data and the information regarding berthing location.

Estimating external costs related to site-specific emissions from both, local and global effects, is a non-trivial undertaking.[8] When doing so it is often referred to Impact Pathway Analysis (IPA) as the most comprehensive methodology by policy makers and the

---

[7] This calculation for all ports was only carried out once for the 2016 data and it was never repeated thereafter as following estimations were only focused on some ports.

[8] For a review of the methodological and empirical state of the art, see Tichavska and Tovar (2017).

scientific community alike. IPA is also followed by several European bottom-up studies for the calculation of external costs related to air emissions from transport in European countries and even sometimes for approximating external costs for shipping or ports. However, it has to be noted that there are methodological differences between those studies with regard to the emission cost calculation pathway. In this paper, BeTa (Netcen, 2004) is followed as it proved to be appropriate for the context at hand in previous studies (Nunes et al., 2019; Tichavska and Tovar, 2015a, b).[9]

BeTa allows among other things to estimate long- and short-term effects of a variety of emissions on mortality and morbidity as well as the effects of SO_2 on buildings and other structures. It should however be noted that some effects are excluded for example non-ozone effects on agriculture and impacts on ecosystems. In addition, Netcen (2004) recognize that there are unknown effects that cannot be included.

It is also recognized that the assumed effects are still subject to a wide variety of research, reaching from detailed analysis of indoor air pollution (Mulenga and Siziya, 2019) to using sensitive plants to evaluate pollution (Benaissa et al., 2019). Also, different indices for air quality have been compared (Motesaddi et al., 2017).

A key assumption in BeTa is that the externalities do not scale linear for larger cities above 500.000 inhabitants (see figures in Table 2). The rationale behind this assumption is (a) that in larger cities other chemical processes take place in the atmospheric layer close to the ground and that (b) larger cities are not as compact as smaller ones and do have a considerable number of parks, lakes, industrial zones and the like. Thus, the cost factor proposed by BeTa depends on the port city population as depicted in Table 2. That is, urban externalities for $PM_{2.5}$ and SO_2 for cities of different sizes are calculated by multiplying results for a city of 100,000 people by the factors shown below.

---

[9] Although Tichavska and Tovar (2015b) and Nunes et al. (2019) followed the same methodology than the one followed in this paper the operational modes considered to calculate the external costs were different: both articles calculated the external costs including the three phases (hotelling, manoeuvring and cruising operations at port) whereas the present study only measures the external costs derived from berthed vessels (hoteling phase). Moreover, not only location (this has been analysed by Tovar and Tichavska, 2019) but also the time when the analysis was done plays a role due to differences and/or changes of regulations (e.g. the limits on sulphur oxides have been progressively tightened). Therefore, the results comparisons among those studies would not yield much insight.

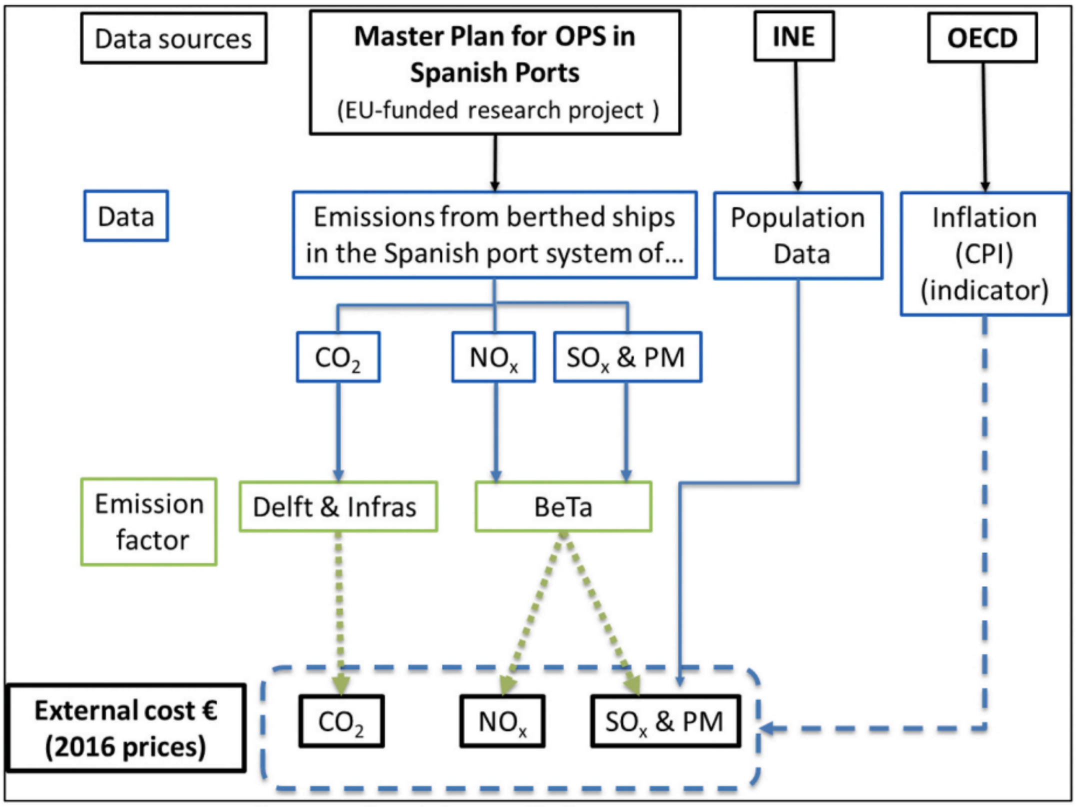
Still, the number of inhabitants is of course a deciding factor for the external cost. Nunes et al. (2019) derivate from BeTa at this point and assume the same external costs for emitted pollutants for cities of 100.000 inhabitants or less which can be thought to be difficult to justify.

With regard to emissions in rural areas, BeTa provides external costs per ton of pollutant for all of the EU-15 countries. The values for Spain are shown in Table 2 for NO_x, SO_x and $PM_{2.5}$.

While the effect of NO_x, SO_x and $PM_{2.5}$ are timewise as well as geographically limited, the effects of CO_2 is in both of those two aspects much broader and therewith more difficult to assess. Moreover, climate costs are generally believed to increase over time, depending on the accumulation in the atmosphere that has already taken place. Therefore, and following the approach of previous research (Tichavska and Tovar, 2015b, 2019), a lower and an upper value for the costs of CO_2 will be presented, corresponding to two different avoidance target scenarios. The lower estimate is produced under the assumption that the EU GHG reduction target for 2020 is met, with a resulting 25 Euro per ton of CO_2. The upper estimate is produced under the assumption that the long-term goal of keeping the concentration of CO_2 in the atmosphere below 450 ppm is met as well as the target to not exceed a temperature rise of more than 2 °C. In this case, the assumed cost per ton of CO_2 is 146 Euro. A conclusive overview of the external cost factors used in this paper is presented in Table 3.

The applied unit cost values of NO_x, SO_2 as well as $PM_{2,5}$ are on the lower end of the scale when compared to values that have been used in other research (see for example Zis et al., 2019).

Another important factor that must be taken into account is that the external costs are reported in prices ranging from 2000 to 2008 (see Table 3). For this reason, the external costs factors for emissions are adjusted for the year under study (2016). This was done, using the Consumer Price Index (CPI) for Spain to adjust country specific cost factor values. The CPI for EU28 (OECD, 2019) was used to adjust non-country specific cost factors. Fig. 2 shows the applied methodology in a flow chart.



Note: INE = Instituto Nacional de Estadistica
Source: Own elaboration

Fig. 2. Flow Chart of Methodology, Note: INE = Instituto Nacional de Estadistica, Source: Own elaboration.

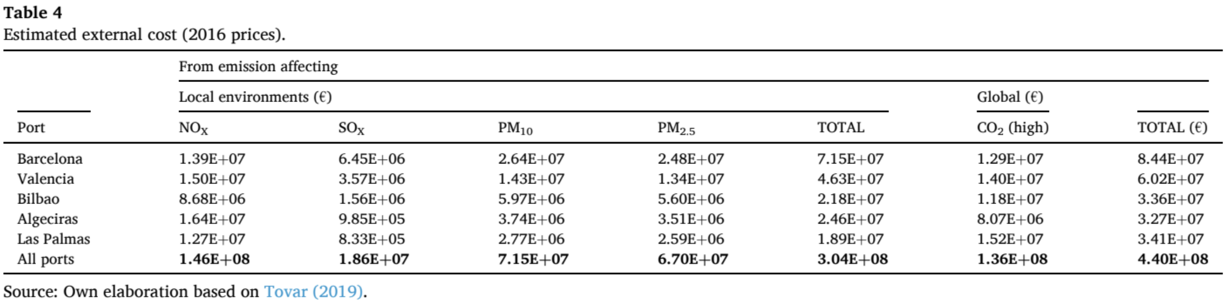


Table 4
Estimated external cost (2016 prices).

	From emission affecting						
	Local environments (€)					Global (€)	
Port	NO_X	SO_X	PM_{10}	$PM_{2.5}$	TOTAL	CO_2 (high)	TOTAL (€)
Barcelona	1.39E+07	6.45E+06	2.64E+07	2.48E+07	7.15E+07	1.29E+07	8.44E+07
Valencia	1.50E+07	3.57E+06	1.43E+07	1.34E+07	4.63E+07	1.40E+07	6.02E+07
Bilbao	8.68E+06	1.56E+06	5.97E+06	5.60E+06	2.18E+07	1.18E+07	3.36E+07
Algeciras	1.64E+07	9.85E+05	3.74E+06	3.51E+06	2.46E+07	8.07E+06	3.27E+07
Las Palmas	1.27E+07	8.33E+05	2.77E+06	2.59E+06	1.89E+07	1.52E+07	3.41E+07
All ports	**1.46E+08**	**1.86E+07**	**7.15E+07**	**6.70E+07**	**3.04E+08**	**1.36E+08**	**4.40E+08**

Source: Own elaboration based on Tovar (2019).

5. Results

The following estimates will depict what the maximum saving potential would be, assuming that all vessels would receive shore power. This of course is a theoretical exercise as it would be hardly feasible and would also come with side effects such as the potential need for new power plants in the vicinity of ports. However, it does provide insights into where the greatest saving potential exist and where it would make most sense to promote the provisioning of shore power supply (for another example of a hypothetical estimation if all ships were to use cold ironing see Chang and Wang, 2012).

Table 4 depicts the external costs from shipping emissions from berthed vessels in Spain on both, local and global level. An initial finding is that the combined external cost from both local and global effects lie between 326.8 million Euro and 439.7 million Euro depending on whether the CO_2 high or low estimation, respectively, is used. In further elaborations, it will be referred to the CO_2 high estimation. Of the total external costs, roughly 31% can be allocated to global effects but the majority of externalities occurs in the direct vicinity of the port in question.

Of those local effects, almost half (48.2%) of the external cost is caused by NO_x. Most of the remaining costs are caused by particulate matter (45.5%) and only 6.1% can be attributed to emissions of SO_x. The relatively low share can be due to the regulations with regard to SO_x emissions (Tichavska et al., 2019; Tovar and Tichavska, 2019).

Evidently, not all external costs can be mitigated by means of cold ironing. It very much depends on how the power on shore is produced. Still, even when considering electricity production on shore by means of oil-fired power plants, those power plants will exhibit greater efficiencies of scale than auxiliary engines on board of vessels. Also, even if power plants emit the same quantity of pollutants than vessels, there would be a reduction of external costs due to the fact that power plants are usually located far away from cities.

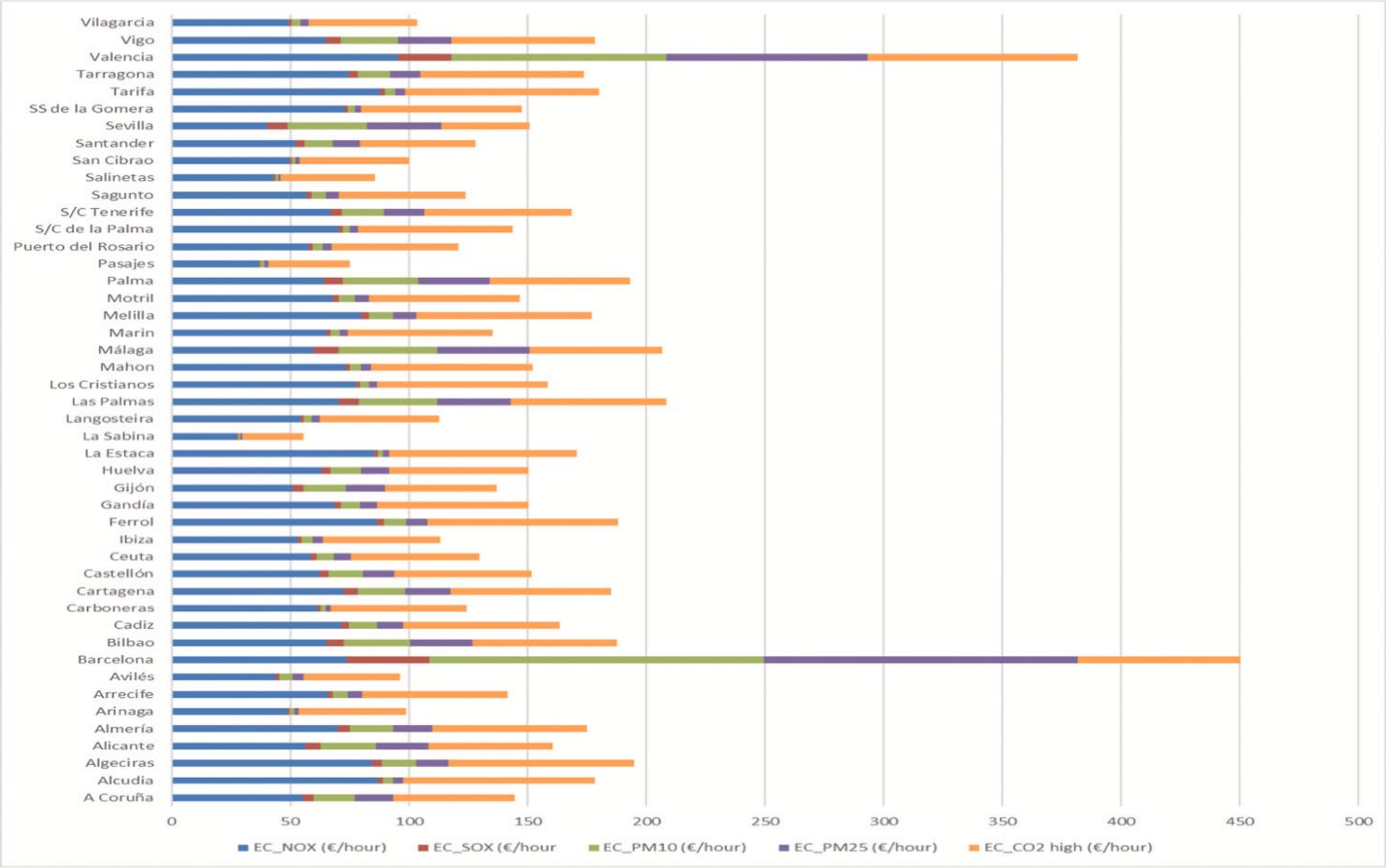
The potential reduction of external costs by means of introducing cold ironing facilities is highest in Barcelona, followed by Valencia as depicted in Fig. 3. Both are important ports for many cargoes as well as passengers. In addition, both cities have a great number of people that could benefit from the improvements introduced by cold ironing. Also, the external costs of vessels at berth could be substantially reduced by introducing cold ironing in Bilbao, Algeciras and Las Palmas de Gran Canaria.

It should be noted that there are substantial differences between the external cost levels even among the top five (see Table 4). Between the first and the second, Barcelona and Valencia respectively, the difference is 24.14 million Euro. Between the second and the third, Valencia and Las Palmas the difference is with 26.14 million Euro even greater. However, the difference between Las Palmas and Bilbao or Las Palmas and Algeciras is only 0.49 and 0.93 million Euro respectively.

Answering why these differences exist is not a trivial undertaking. The amount of external costs is not solely dependent of the population. This factor has no influence on the rural part of the calculation and it is by itself only relevant for the local effect related to SO_x and PM but not NO_x. Furthermore, the shipping activities that can be observed in the various regions are rather heterogeneous and this not only concerns the type of ship (read: type of cargo or type of passenger's vessel) but even within those different types, the ages and sizes of the ships in question are key contributing factors. To address this matter and account for the apparent heterogeneity, it is necessary to introduce eco-efficiency indicators, which are presented in Figs. 3 and 4.

Note: Total external cost figures are calculated based on the CO_2 high estimation
Source: Own elaboration

Fig. 3. Total external costs per port corresponding to the reduction in annual gas emissions if electricity was supplied to vessels at berth in 2016. Note: Total external cost figures are calculated based on the CO_2 high estimation. Source: Own elaboration.



Source: Own elaboration

Fig. 4. Eco-efficiency: External cost at berth of each pollutant and port 2016 (€/hour).

Source: Authors

Fig. 4 depicts the external costs at berth of each pollutant and port on a Euro per hour basis. Introducing these eco-efficiency indicators helps in untangling the relation of port stay duration and a potential linkage to ports themselves (factors related to the port can influence how long a vessel stays in a port).

While Valencia and Barcelona are also experiencing the highest amount of external costs per hour, new insights can be derived from the eco-efficiency indicators presented in Fig. 4. For instance, Barcelona and Valencia are both important ports. With reference to Table 1, it can be said that Valencia has a considerably higher amount of containerized cargo whereas Barcelona has a higher amount of general cargo. This pattern continues for example with cruise passengers where Barcelona is more important than Valencia and is even more apparent with solid bulk and non-cruise passengers where Valencia does not even appear in the top 10. However, the external costs per hour that can be allocated to NO_x and CO_2 are higher in Valencia than in Barcelona. In this respect, it has to be noted again that the external cost of NO_x and CO_2 are independent of the population. With respect to the other pollutants Barcelona always exhibits higher external cost, which might be due to the fact that Barcelona has almost twice the number of inhabitants than Valencia. The same can be said about the external cost per ship.

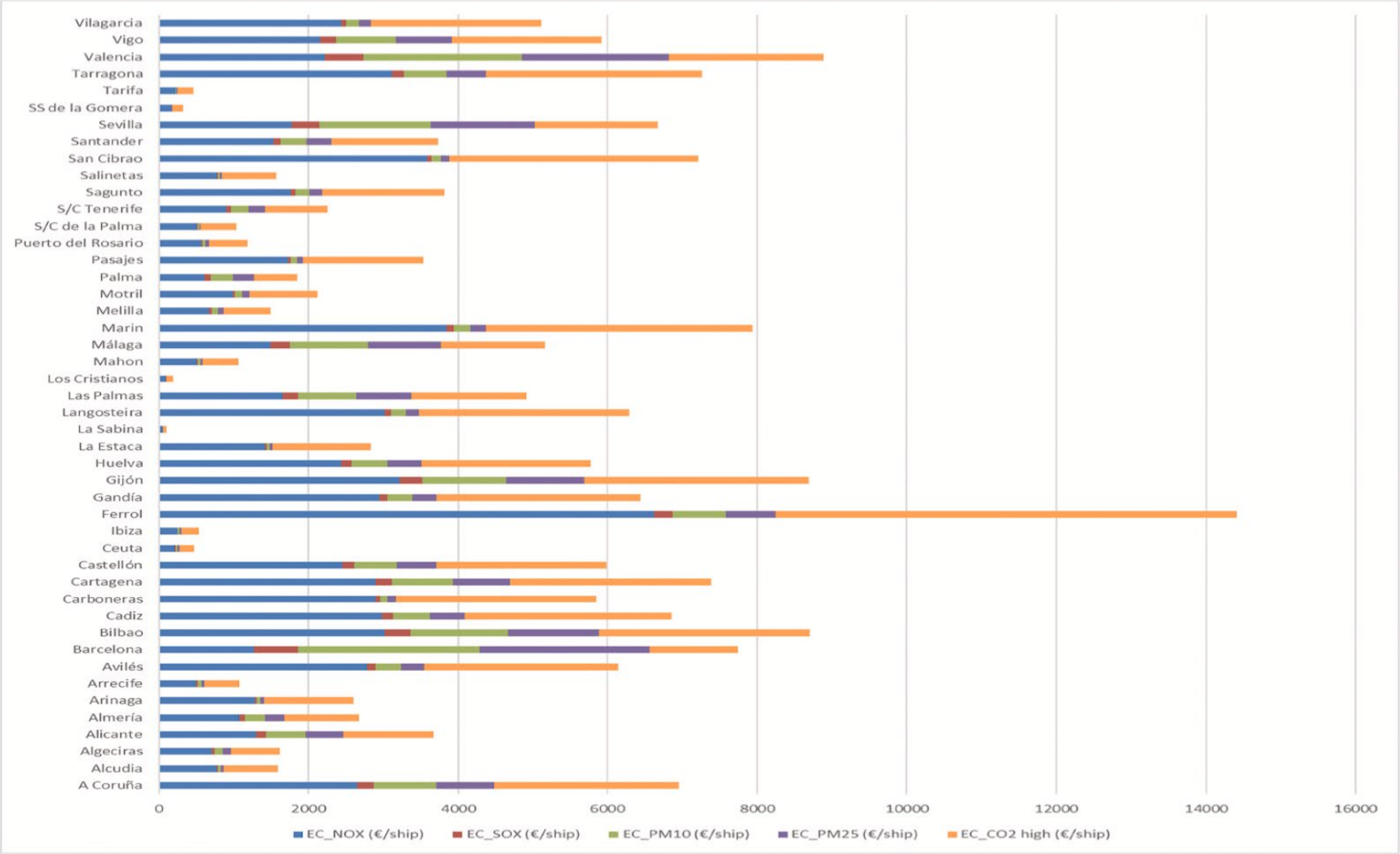
The effect population has become even clearer when Algeciras and Barcelona are compared. Again, the external costs per hour that can be allocated to NO_x and CO_2 are higher in Algeciras but with regard to all other pollutants the external costs are higher in Barcelona.

A comparison of ports with a relatively similar population can be thought to be useful. Malaga and Seville have a population of 569,009 and 690,566 respectively. The external costs for Malaga and Seville are 9.6 and 13.7 million Euro respectively. In general, Seville has more traffic in all categories than Malaga except for non-cruise passengers where Seville has none and cruise passengers where Malaga also has significantly more traffic. Still, Malaga experiences higher external costs per hour.

Generally speaking, it can be said that the eco-efficiency external costs per hour has considerably less spread than the eco-efficiency external costs per ship as depicted in Fig. 5. The most apparent reason for that is that the amount of external costs generated per hour is in and by itself within much tighter boundaries than the time that vessels may stay in a given port.

The port stay time of a given vessel also depends on a variety of factors. A general rule of thumb for cargo vessels is that a smaller vessel can be discharged quicker than a larger vessel. However, this is not always the case. This can be attributed to the fact that more cargo handling equipment can be working simultaneously on larger vessels. Also, it can be noted that bulk vessels of the same size as container vessels are considerably slower to be discharged. This is very well reflected by the fact that for example Gijon, the port with the highest throughput of solid bulk, is one of the ports with the highest external cost per ship call.

Apart from the port stay time that can be seen as a major contributing factor to the considerable variation in external costs per vessel calling a port, it is also the vessels themselves that have different properties, causing higher or lower external costs per port call. Such properties are related to age, size and mere type of vessel, most prominently the differentiation between cruise and non-cruise vessels. This effect, however, is not as noticeable in the data as many confounding factors play a role such as the population in the direct vicinity of the port and the fact that many ports that receive a high number of calls from cruise vessels also receive a high number of calls from non-cruise vessels.



Source: own elaboration

Fig. 5. Eco-efficiency: External cost at berth of each pollutant and port 2016 (€/ship)

Source: Authors

6. Conclusion

It has been calculated that cold-ironing reduces total shipping-related greenhouse gases by less than 0.5%; though of greater importance are the benefits related to SO_x, NO_x and PM reductions and improvement in local air quality (Cullinane and Cullinane, 2019). Therefore, not only the environment but also the local population living near the port could obtain a benefit which can be calculated as a monetary equivalent of avoided damage by the effects of ship emission.

The result of this work provides a Spain-wide insight into where, on a port by port level, the highest externalities exists and where the introduction of cold ironing could yield the highest potential on reducing said externalities. To the best of the knowledge of the authors, this is the first time a Spain-wide analysis of external costs and the associated saving potential of cold ironing was conducted.

Based on the analysis, three main observations can be made:

Firstly, population plays a key role in the estimation of external costs but does not explain all. In particular, when considering the indicator 'external cost by ship' one can observe that the obtained values are always higher for Seville than Malaga even though it clearly is the other way around for external costs per hour.

Secondly, the activity or rather the composition of the traffic plays an important role, which also shows in the difference of two of the commonly used metrics of port activity: berth hours and ship calls. In this respect, it must be noted that the indicator berth hour is a homogenous measure while ships are not. This is due to the fact that ships cannot only differ in age and size but also in type. Essentially, a container vessel has to be treated as an entirely different entity than a cruise ship or a ferry.

Thirdly and potentially most importantly, if one sets out to fully understand the different aspects of sustainability in a port, there is a clear need for an individually tailored analysis of the port with a much more refined analysis that includes the eco-efficiency indicators by hours and also by type of ship. This also can be seen as a clear area for future research as well as a contribution to the existing body of literature.

While the recommendation of specific policy measures is beyond the scope of this document, it should be noted that the presented findings can contribute in a significant way to the potential introduction of new rules and regulations in the Spanish port sector. As it was shown in the literature review, introducing cold ironing is one of the most expensive abatement technologies. If only the global impact of shipping emissions is considered, the relatively high cost of installing cold ironing facilities in ports, would not make it appear as a very attractive abatement technology. The here presented findings underline the importance of local effects, in particular when they are considered as external costs.

Internalization of those external costs has been a challenge for policy makers for a substantial amount of time. This is due to the fact that rules and regulations should have a sound basis that is backed up by evidence, in order to avoid unforeseen consequences brought from wrong incentives derived from poorly designed policies. The here presented results can serve as such basis as they are already providing a good insight into the relationship between population size, traffic mix and external costs. Furthermore, the introduced eco-efficiency indicators can help to support the introduction of new policy measures such as, for example, emission trading between ports.

A clear limitation of the here conducted research was that the feasibility of installing cold-ironing facilities in ports has not been addressed. Also, it is acknowledged that the obtained estimates are still surrounded by a good amount of uncertainty. A contributing factor to the mentioned uncertainty is related to the external cost factors that are based on previous studies (BeTa) and generally considered out of scope in studies like this.

Finally, it should be noted that the potential reduction of external costs by means of introducing cold ironing facilities is even greater than the one estimated in this study since other externalities (e.g. noise) were not included in the calculation.

While this document offers insights into many different aspects of external costs in the Spanish port system and their potential abatement through cold ironing, there are still things left for future research. As it was shown, there are clear differences when external costs are considered in terms of eco-efficiency indicators. Future research should address how those differences come to exist. One potential aspect that should be considered is the vessel type, read container, bulk, Roll-On Roll-Off, cruise vessel, as it is very likely to play a major role in terms of impact on the here introduced eco-efficiency indicators.

Credit author statement

Thomas Spengler: Conceptualization, Methodology, Software, Writing – original draft.
Beatriz Tovar: Conceptualization, Methodology, Data collection, Software, Supervision, Writing-Reviewing and Editing

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Financial assistance for this work was provided by PROJECT 2015-EU-TM-0417 OPS MASTER PLAN FOR SPANISH PORTS Grant NEA/CEF/TRAN/M2015/1128.

Notation

SLCP Short-Lived Climate Pollutant
BETA Benefits Table database
NEEDS New Energy Externalities Development for Sustainability
CAFE Clean Air for Europe
SECA Sulphur Emission Control Area
IPA Impact Pathway Analysis
GHG Greenhouse gases
IMO International Maritime Organization
MDO Marine Diesel Oil
MGO Marine gasoil
CPI Consumer Price Index
E Emissions in tons for pollutant i
AE Auxiliary engine power in kilowatt
t time
FE emission factor for pollutant i in tons per kilowatt-hour
AIS Automatic Identification System

7. References

Adamo, F., Andria, G., Cavone, G., De Capua, C., Lanzolla, A.M.L., Morello, R., Spadavecchia, M. 2014. Estimation of ship emissions in the port of Taranto. Measurement 47, 982–988. doi: 10.1016/j.measurement.2013.09.012.

Ballini, F., Bozzo, R. 2015. Air pollution from ships in ports: the socio-economic benefit of cold-ironing technology. Res. Transp. Bus. Manag. 17, 92–98. doi: 10.1016/j.rtbm.2015.10.007.

Benaissa, F., Bendahmane, I., Bourfis, N., Aoulaiche, O., Alkama, R., 2019. Bioindication of urban air polycyclic aromatic hydrocarbons using petunia hybrida. Civ. Eng. J. 5. doi: 10.28991/cej-2019-03091333.

Chang, C.C., Wang, C.M. 2012. Evaluating the effects of green port policy: case study of Kaohsiung harbor in Taiwan. Transport. Res. Transport Environ. 17, 185–189. doi: 10.1016/j.trd.2011.11.006.

Chatzinikolaou, S.D., Oikonomou, S.D., Ventikos, N.P. 2015. Health externalities of ship air pollution at port–Piraeus port case study. Transport. Res. Transport Environ. 40, 155–165. doi: 10.1016/j.trd.2015.08.010.

Cullinane, K., Cullinane, S. 2019. Policy on reducing shipping emissions: implications for "green ports". In: Bergquist, R., Monios, J. (Eds.), Green Ports. Inland and Seaside Sustainable Transportation Strategies. Elsevier Inc., pp. 35–62. doi: 10.1016/B978-0-12-814054-3.00003-7

Dai, L., Hu, H., Wang, Z., Shi, Y., Ding, W. 2019. An environmental and techno economic analysis of shore side electricity. Transport. Res. Transport Environ. 75, 223–235. doi: 10.1016/j.trd.2019.09.002.

Davarzani, H., Fahimnia, B., Bell, M., Sarkis, J. 2016. Greening ports and maritime logistics: a review. Transport. Res. Transport Environ. 48, 473–487. doi: 10.1016/j.trd.2015.07.007.

Delft, C.E., Infras, F.I. 2011. External Costs of Transport in Europe. Update Study for 2008. Commissioned by. International Union of Railways UIC, Delft, CE. Delft, September, p. 2011.

Denisis, A. 2009. An Economic Feasibility Study of Short Sea Shipping Including the Estimation of Externalities with Fuzzy Logic. Ph.D. Thesis. The University of Michigan, USA.

European Maritime Safety Agency, 2016. Information for State Authorities, Ship Owners, Masters, Fuel Suppliers, Agents or Operators of Ships on Directive 1999/32/EC.

European Parliament and Council, 2016. Directive (EU) 2016/802 of the European Parliament and of the Council of 11 May 2016 Relating to a Reduction in the Sulphur Content of Certain Liquid Fuels. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32016L0802. (Accessed 14 November 2018).

European Parliament, 2018. European Parliament Resolution of 25 October 2018 on Deployment of Infrastructure for Alternative Fuels in the European Union: Time to Act! (2018/2023(INI)). European Union.

IDAE. Announces on-shore power will be addressed by new electricity regulation to avoid air pollution from ships at berth. http://poweratberth.eu/?p=2033&lang=en. (Accessed 19 November 2018).

Innes, A., Monios, J. 2018. Identifying the unique challenges of installing cold ironing at small and medium ports–The case of aberdeen. Transport. Res. Transport Environ. 62, 298–313. doi: 10.1016/j.trd.2018.02.004.

Kachi, A., Mooldijk, S., Warnecke, C. 2019. Carbon pricing options for international maritime emissions. Available at: https://www.carbon-mechanisms.de/fileadmin/media/dokumente/Publikationen/Studie/Carbon-pricing-options-for-international-maritime-emissions.pdf. (Accessed 14 November 2018).

Kumar, J., Kumpulainen, L., Kauhaniemi, K. 2019. Technical design aspects of harbour area grid for shore to ship power: state of the art and future solutions. Int. J. Electr. Power Energy Syst. 104, 840–852. doi: 10.1016/j.ijepes.2018.07.051.

Main Spanish shipping liners, 2019. Operating in Canary Archipelago Will Be provided with OPS in Spring Next Year. Available at: http://poweratberth.eu/?p=2003&lang=en. (Accessed 10 October 2018).

Maragkogianni, A., Papaefthimiou, S. 2015. Evaluating the social cost of cruise ships air emissions in major ports of Greece. Transport. Res. Transport Environ. 36, 10–17. doi: 10.1016/j.trd.2015.02.014.

Merk, O. 2014. Shipping emissions in ports. Int. Transp. Forum (2014–20). Discussion Paper.

Motesaddi, S., Hashempour, Y., Nowrouz, P. 2017. Characterizing of air pollution in Tehran: comparison of two air quality indices. Civ. Eng. J. 3 (9), 749–758. doi: 10.21859/cej-030911.

Mulenga, D., Siziya, S. 2019. Indoor air pollution related respiratory ill health, a sequel of biomass use. Sci. Med. J. 1 (1), 30–37. doi: 10.28991/SciMedJ-2019-0101-5.

Netcen. 2004. Benefits table database: estimates of the marginal external costs of air pollution in Europe. BeTa version E1.02a. Created for European Commission DG Environment by Netcen.

Nunes, R.A.O., Alvim-Ferraz, M.C.M., Martins, F.G., Sousa, S.I.V. 2019. Environmental and social valuation of shipping emissions on four ports of Portugal. J. Environ. Manag. 235, 62–69. doi: 10.1016/j.jenvman.2019.01.039.

OECD, 2019. Inflation (CPI) (Indicator). doi: 10.1787/eee82e6e-en.

Pettit, S., Wells, P., Haider, J., Abouarghoub, W. 2018. Revisiting history: can shipping achieve a second socio-technical transition for carbon emissions reduction? Transport. Res. Transport Environ. 58, 292–307. doi: 10.1016/j.trd.2017.05.001.

Rodriguez-Alvarez, A., Tovar, B. 2012. Have Spanish port sector reforms during the last two decades been successful? A cost frontier approach. Transport Pol. 24, 73–82. doi: 10.1016/j.tranpol.2012.06.004.

Sciberras, E.A., Zahawi, B., Atkinson, D.J. 2015. Electrical characteristics of cold ironing energy supply for berthed ships. Transport. Res. Transport Environ. 39, 31–43. doi: 10.1016/j.trd.2015.05.007.

Smith, T.W.P., Jalkanen, J.P., Anderson, B.A., Corbett, J.J., Faber, J., Hanayama, S., 2015. Third IMO GHG Study 2014–executive Summary and Final Report. Int. Maritime Organization (IMO).

Styhre, L., Winnes, H., Black, J., Lee, J., Le-Griffin, H. 2017. Greenhouse gas emissions from ships in ports–Case studies in four continents. Transport. Res. Transport Environ. 54, 212–224. doi: 10.1016/j.trd.2017.04.033.

Tichavska, M., Tovar, B. 2015a. Port-city exhaust emission model: an application to cruise and ferry operations in Las Palmas Port. Transport. Res. Part A Policy Pract. 78, 347–360. doi: 10.1016/j.tra.2015.05.021.

Tichavska, M., Tovar, B. 2015b. Environmental cost and eco-efficiency from vessel emissions in Las Palmas Port. Transport. Res. E Logist. Transport. Rev. 83, 126–140. doi: 10.1016/j.tre.2015.09.002.

Tichavska, M., Tovar, B. 2017. External costs of vessel emissions at port: a review of the methodological and empirical state of the art. Transport Rev. 37, 383–402. doi: 10.1080/01441647.2017.1279694.

Tichavska, M., Tovar, B. Gritsenko, D., Johansson, L., Jalkanen, J.-P., 2019. Air emissions from ships in port: does regulation make a difference? Transp. Policy 45, 128–140. doi: 10.1016/j.tranpol.2017.03.003.

Tovar, B. 2019. External Cost Per Spanish Port Corresponding to the Reduction in Annual Gas Emissions if Electricity Was Supplied to Vessels at Berth. OPS Master Plan for Spanish Ports Project. Final Report. http://poweratberth.eu/?page_id=120&lang=en. (Accessed 2 February 2019).

Tovar, B., Tichavska, M. 2019. Environmental cost and eco-efficiency from vessel emissions under diverse SOx regulatory frameworks: a special focus on passenger port hubs. Transport. Res. Transport Environ. 83, 126–140. doi: 10.1016/j.trd.2019.01.019.

Tovar, B., Wall, A. 2017. Competition strategies in the Spanish port system in recent decades and their relation with port authority efficiency. In: Pettit, S., Beresford, A. (Eds.), Port Management: Cases in Port Geography, Operations and Policy. P Kogan Page Ltd. United Kingdon, pp. 376–406. http://hdl.handle.net/10553/55669.

Tovar, B., Wall, A. 2019a. Are larger and more complex port more productive? An analysis of Spanish port authorities. Transport. Res. Part A Policy Pract. 121, 265–276. doi: 10.1016/j.tra.2019.01.008.

Tovar, B., Wall, A. 2019b. Environmental efficiency for a cross-section of Spanish port authorities. Transport. Res. Transport Environ. 75, 170–178. doi: 10.1016/j.trd.2019.08.024.

Tovar, B., Wall, A. 2020a. The External Costs of Port Activity for Port Cities: an Environmental Efficiency Analysis of Spanish Ports. Working Paper. Las Palmas University, Spain.

Tovar, B., Wall, A. 2020b. Regulation and finance in the Spanish port sector. In: Haralambides, H., Tei, A., Ferrari, C. (Eds.), Regulation and Finance in the Port Industry: Lessons from Worldwide Experiences. Palgrave. Forthcoming.

Wan, Z., El Makhloufi, A., Chen, Y., Tang, J. 2018. Decarbonizing the international shipping industry: solutions and policy recommendations. Mar. Pollut. Bull. 126, 428–435. doi: 10.1016/j.marpolbul.2017.11.064.

Wu, L., Wang, S. 2020. The shore power deployment problem for maritime transportation. Transport. Res. E Logist. Transport. Rev. 135, 101883. doi: 10.1016/j.tre.2020.101883.

Zis, T., North, R.J., Angeloudis, P., Ochieng, W.Y., Bell, M.G.H. 2014. Evaluation of cold ironing and speed reduction policies to reduce ship emissions near and at ports. Marit. Econ. Logist. 16, 371–398. doi: 10.1057/mel.2014.6.

Zis, T., Angeloudis, P., Bell, M.G., Psaraftis, H.N. 2016. payback period for emissions abatement alternatives: role of regulation and fuel prices. Transport. Res. Rec. 2549, 37–44. doi: 10.3141/2549-05.

Zis, T.P. 2019. Prospects of cold ironing as an emissions reduction option. Transport. Res. Part A Policy Pract. 119, 82–95. doi: 10.1016/j.tra.2018.11.003.

Chapter 3: Environmental valuation of in-port shipping emissions per shipping sector on four Spanish ports

1. Introduction

Understanding and potentially mitigating the negative impact of transport on the well-being of people living close to major infrastructure hubs is a critical challenge in the upcoming decades. This paper aims to contribute to a potential solution by providing insights into the external costs associated with berthed vessels in four ports in Spain: Tenerife, Las Palmas de Gran Canaria, Palma de Mallorca, and Pasaia. Local as well as global external costs will be presented.

Apart from the value that lies in providing figures for these four ports, this work also contributes to the existing body of literature in a broader sense. The here presented findings can be further used to estimate the impacts shipping in ports has on the cities in the vicinity. The here conducted research differentiates external costs by vessel type which also allows for more finely grained adjustments to policies and port management strategies. Furthermore, existing measurements of external costs are improved and expanded upon by the here presented results.

The key distinction that must be made in the case of local and global effects lies in the scope, not only spatial but also temporal. Global effects are mostly associated with carbon dioxide (CO_2) that remains for a considerable time in the atmosphere and lead to global warming and climate change (IPCC, 2018). Local effects, often associated with particulate matter (PM), nitrogen oxide (NO_x) and sulphur oxides (SO_x), stay in the vicinity of the source of emission and are harmful to humans' health (Vianna et al., 2020). Estimating the external costs associated with those local effects has been the subject of a wide variety of research during the past years (Tzannatos, 2010a, 2010b; Tovar and Tichavska, 2019;

Nunes et al., 2019). While the level of uncertainty in the estimations is still significant the results can provide valuable insights.

For cities or regions in the direct vicinity of sea ports, the external costs of those ports are a major concern. Therefore, it is not surprising that several stakeholders from the public and private sector are interested in knowing the external costs related to ship operations in general and the effect potential abatement technologies such as cold ironing[10] could have on external costs (Chatzinikolau et al., 2015). Cold ironing provides electric energy from the shore to the vessels. Electricity generation on board of vessels almost exclusively works through diesel generators and the associated emissions and therewith the associated negative impact of exhaust gases occurs directly in the port. The benefit of cold ironing technology lies in how and where energy is produced. Firstly, power supplied from shore, can come from renewable sources which will automatically reduce external costs. Secondly, even if not, the much larger power plants ashore are benefitting from efficiencies of scale when compared to relatively small diesel generators on board of vessels. In addition to that, large coal or diesel power plants are usually located further away from the city. This will ultimately lead to less people exposed to the emissions and therewith to lower external costs.

This goes hand in hand with regulatory efforts aiming at reducing pollution from vessels. One of the most known ones is the Convention for the Prevention of Pollution for Ships (MARPOL 73/78) which was introduced by the International Maritime Organization already in 1973. This regulation was further developed to account for new knowledge about the effects of different pollutants as well as technological advancements. In particular Annex VI of MARPOL has to be mentioned as it was introducing incrementally lower limits for sulfur content of fuel in all areas of the world and even lower limits in designated Emission Control Areas (ECA). The European Union and the United States have introduced further limits and regulations for the sulfur content of fuel in particular for vessels at berth. Diesel fuel with the required low sulfur limits is considerably more

---

[10] A detailed analysis about the cold ironing is out of the scope of this article but a recent review regarding this issue could be found in Spengler & Tovar (2021). The interested reader could also see Sciberras, et al. (2015); Zis et al. (2015) and Zis (2019).

expensive which might offset the additional costs for fitting vessels with cold ironing facilities to a certain extent.

As a result of the interest mentioned above, several initiatives can be found. One of them is the On-Shore Power Supply (OPS) Master Plan for Spanish ports, which aims to draft a Master Plan for the supply of electric power to ships at berth in Spanish Ports. This paper will focus on the four ports which were the first to become involved in the OPS project

The current pandemic has had significant impact on the life of everyone and on the shipping industry. In particular, the cruise industry is faced with unprecedented difficulties as cruise vessels are perceived to contribute to the spread of COVID-19 (Ito et al., 2020). At the time of writing, it is unclear how long the global pandemic will have an impact and if specific behavioural changes of people will persist even after COVID-19 has been overcome. Independent of how the situation will evolve, it can be expected that the impact of COVID-19 on the shipping industry in general, and the external costs in seaports in particular, will be subject to future research. Even an impact on port management and governance could be expected (Notteboom and Haralambides, 2020).

A prerequisite for conducting such comparative research is a profound analysis of the situation in a pre-COVID setting. Hence, this work provides an insight into the external costs associated with ship calls in four Spanish ports before COVID-19 was on the agenda. First, on a port-by-port level. Second, on the level of the individual vessel types as this can also provide valuable insights. Furthermore, relative indicators will be introduced to give more insights into the relationships between ship types and external costs.

The work is structured as follows: first an overview of the relevant literature is given. This is followed by a section elaborating on the methodological approach and the material that was used in the preparation of this document. In continuation, the results for the four ports in question will be presented, first from an overall perspective and then from the perspective of relative indicators. After that, a conclusion and an overview of possible further research will be provided.

2. Brief literature review and problem statement

A recent review of the studies analysing the impact of harbour activities on port cities air quality (Sorte et al., 2020) has shown the relevant contribution of those activities in terms of concentrations of the main critical pollutants, namely PM_{10}, $PM_{2.5}$, NO_2 and SO_2. Those pollutants are affecting human health and causing others environmental damage such as, a decrease in biodiversity and crop yield, damage to materials and building surfaces, to name a few.

Estimating a monetary value to assess the impact of pollution on humans, the environment and the property is not an easy task. It is intertwined with many factors ranging from personal preferences to considerable difficulties obtaining accurate data. However, they have several applications for policy use in port-cities such as, for example, their utility as indicators that a port should deserve more attention (Nunes et al., 2019) and/or to apply taxes or special fees as an incentive to ensure that best environmental practices are observed (Tichavska and Tovar, 2015; Tovar and Tichavska, 2019). What is more, they also can be used to investigate whether ports could reduce external costs derived from the exhaust emissions while maintaining their level of service (readers interested in the environmental efficiency analysis of Spanish ports can consult Tovar & Wall, 2019, 2021). Therefore, despite the difficulties it be worth to calculate them.

As a comprehensive review of the extant literature has shown (Tichavska and Tovar, 2017[11]), during the past years, the impact pathway approach (IPA) has developed into a de facto standard for estimating external costs associated with air emissions. Major European bottom-up studies such as (1) BeTa, (2) CAFE, (3) HEATCO and (4) NEEDS followed IPA for the estimation of external costs in transport.

(1) The Benefits Table (BeTa) methodology provides external cost figures for several pollutants. Namely NO_x, $PM_{2,5}$, SO_2 and VOCs. A general differentiation that is done by BeTa is the one of location where the emission occurs. The differentiation is done between rural, urban and shipping. In the case of shipping, also a differentiation is done between

---

[11] This brief literature review is made only to place our paper into the proper context. For a recent review of the methodological and empirical state of the art about the external cost estimation from in-port emissions released by vessels see Tichavska and Tovar (2017)

four different waters (Eastern Atlantic, Baltic Sea, English Channel, Northern Mediterranean and North Sea).

As for the emissions on shore, the specific external cost factors are provided for rural areas by country, covering 15 European countries. As for the emissions in urban areas, there is no disaggregation done on a country level. The differentiation for urban areas takes place depending on the number of inhabitants for $PM_{2.5}$ and SO_2. It is assumed that the external costs increase linearly for up to 500.000 inhabitants and after does it in a lower proportion (non-linear). For “several million people” and above, a maximum for external costs and no marginal increase is assumed. This is based on processes in atmospheric layers close to the ground as well as a higher number of parks and lakes in large cities which lead to no further increase in population density.

As for the effects that are considered, again a relatively finely grained set of features from a variety of sources is considered in order to estimate the external costs. By way of example, the effect SO_2 has on buildings and other structures is considered.

A comprehensive overview of the relevant literature is provided in Table 1.

Table 1: Comprehensive overview of the literature.

Paper	Area	Scale	Timeframe	Shipping sector	Vessel state	Methodology
Miola et al. (2009)	Italy	Port	2006	passenger and cargo	curising	CAFE
Tzannatos (2010a)	Greece	Port	2008-2009 (12 months)	passenger and cruise	manoeuvering and at berth	BeTa
Tzannatos (2010b)	Greek Sea	Regional	1984-2008	domestic and international shipping	cruising	BeTa
Berechman and Tseng (2012)	Kaoshiung (Taiwan)	Port	2010	bulk, container,general cargo, barges, tankers, fishing ships, work boats and tugboats	at berth	BeTa
Castells et al. (2014)	Selected Spanish ports	Regional	2009	Ro-Ro, passenger, and container ships	hotelling and manoeuvring	BeTa
McArthur and Osland (2013)	Bergen (Norway)	Port	2010	entire fleet	at berth	BeTa, CAFE and several studies
Song (2014)	Yangshan (China)	Port	2009	entire fleet	hotelling, manoeuvring and cruising	Based on several Top-Down studies
Maragkogianni and Papaefthimiou (2015)	Piraeus, Santorini, Mykonos, Corfu and Katakolo	Port	2013	cruise	hotelling and manoeuvring	CAFE and NEEDS
Tichavska and Tovar (2015b)	Las Palmas (Spain)	Port	2011	entire fleet	hotelling, manoeuvring and cruising	BeTa, CAFE and NEEDS
Dragović et al. (2015)	Dubrovnik and Kotor (Croatia)	Port	2012-2014	cruise	at berth and at anchor	NEEDS
Tovar and Tichavska (2019)	Las Palmas (Spain), St. Petersburg (Russia) and Hong Kong	Port	2011-2012	entire fleet	at berth	BeTa
Nunes et al. (2019)	Leixões, Setúbal, Sines and Viana do Castelo (Portugal)	Port	2013	entire fleet	hotelling and manoeuvring	BeTa, CAFE and NEEDS

Source: Own elaborations based on Tichavska and Tovar (2017)

Tzannatos (2010a) analysed the emissions and associated externalities in the port of Piraeus and later (Tzannatos, 2010b) analysed the shipping emissions and externalities for all of Greece. The BeTa based approaches lead to findings indicating that the external costs associated with shipping reach 51 million Euro per year in Piraeus alone and 2.95 billion Euro per year in the entirety of Greece.

McArthur and Osland (2013) applied amongst other studies also BeTa to the port of Bergen in Norway. According to their application of BeTa, the external costs of ships at berth in the port of Bergen reach approximately 6.07 million Euro per year.

Castells et al. (2014) estimated the external costs in the Spanish port system applying, similar to McArthur and Osland (2013), BeTa and CAFE. They calculated emissions per following three types of vessels: passenger, Ro-Ro and container and reported the share of emissions are 41%, 33% and 25% respectively.

Tichavska and Tovar (2015) estimated external costs through BeTa as well as other methodological approaches for the port of Las Palmas de Gran Canaria and introduced the following eco-efficiency indicators: external costs per passenger, per ton of cargo, per ship call and per port revenue. They estimated the overall external costs for Spain to be 174 million Euro for 2011.

Nunes et al. (2019) analysed the ports of Leixões, Setúbal, Sines and Viana do Castelo in Portugal and applied among other methodological approaches BeTa and used for further analysis of local external costs BeTa and the average of the sensitivity scenarios. They found that Sines and Setúbal were the ports with the highest estimated external costs with 200 million Euro and Viano do Castelo was the port with the lowest estimated external costs with only 6.3 million Euro.

Finally, Tovar and Tichavska (2019) analysed three ports that are under different regulatory regimes. The methodological challenge of applying cost factors from BeTa to non-European countries was solved by utilizing the EU15 average. They estimated the external costs to be 2311 million Euro, 779 million Euro and 7423 million Euro in Las Palmas de Gran Canaria, St. Petersburg and Hong Kong respectively.

(2) The Clean Air for Europe (CAFE) methodology provides external cost figures for NH_3, NO_x, $PM_{2,5}$, SO_2 and VOCs disaggregated by land (EU25 excluding Cyprus) and the corresponding sea areas.

A general challenge in designing a model for capturing externalities is the difficulty on setting boundaries and deciding what to account for and what not. In the justification of the design of CAFE, it was argued that they considered chiefly those factors that are likely to have a substantial effect on the outcome of the computations while the ones that were not believed to have a significant effect were omitted.

Still, also in the design of CAFE it was admitted that there are factors where it just could not be said whether they have a substantial impact or not. A prime example for this is the chronic health impact ozone has on humans. Due to lack of reliable data, said impact was omitted.

In addition to that, it was recognized that in a given application of the CAFE methodology one might be inclined to consider a set of inputs to be more suitable than another given set. To account for that, external cost figures were provided for a number of combinations. Namely, the value of a life year (VOLY) could be either taken from the median or the mean. Also, instead of the VOLY, one could consider the value of a statistical life (VSL), which naturally is considerably higher. Then again, also the VSL numbers could be taken for the median or the mean.

To add to the already relatively complex picture, the effect of ozone on health below a threshold of 35 ppm is apparently not fully investigated. Also, non-ozone related health impact is divided into two subsets in the CAFE methodology: a core set of functions, that is considered robust and a “sensitivity” set of functions, that is considered to be less robust.

Overall, the number of combinations that could arise from the given considerations would be overwhelming if one would still want to introduce a methodology where the results of the applications could still be compared with each other. To account for that external cost, numbers were only provided for four possible combinations, or scenarios. Namely: (1) VOLY median for PM and Ozone mortality, only the set of health functions and a threshold for ozone at 35 ppm. (2) VSL median for PM mortality, VOLY median for ozone mortality, core health functions and a threshold for ozone at 35 ppm. (3) VOLY mean for PM and Ozone mortality, sensitivity health functions and no threshold for ozone. (4) The same as (3) but with VSL mean for PM mortality.

CAFE was also applied in numerous studies (Castells et al., 2014; McArthur and Osland, 2013; Tichavska and Tovar (2015); Maragkogianni and Papaefthimiou, 2015; Tovar and Tichavska, 2019; Nunes et al., 2019).

McArthur and Osland (2013) also applied the CAFE approach to the port in Bergen and reported that the external costs per year in Bergen for ships at berth reached 4.75 million Euro when estimated through CAFE. That is a substantially lower figure than the BeTa figure as discussed earlier.

Tichavska and Tovar (2015) also applied CAFE and reported, depending on the sensitivity scenario, a variation of between -8% to +18% when compared to the results that were obtained from only BeTa. Given the complexity CAFE adds, it is deemed appropriate to compare the results of CAFE + BeTa with only BeTa to see if substantial changes can be observed. Castells et al. (2014), Tovar and Tichavska (2019) and Nunes et al. (2019) also followed this approach when analysing Spanish ports, three ports that are under different regulatory regimes and four ports in Portugal, respectively.

Finally, Maragkogianni and Papaefthimiou (2015) focused only on cruise ships in the ports of Piraeus, Santorini, Mykonos, Corfu and Katakolo in Greece. They applied CAFE and NEEDS and estimated that the health impact from cruise shipping can be as high as 5.3 Euro per passenger.

(3) The Harmonised European Approaches for Transport Costing and Project Assessment (HEATCO) is, as the name suggests, aimed specifically at transport and infrastructure projects. The objective of HEATCO is to offer a “set of harmonised guidelines for project assessment and transport costing”.

HEATCO was intentionally and from the beginning set up to cover a wide range of different concerns, reaching from valuation of congestion and accident risk reduction to infrastructure cost as well as external cost.

It lies in the very nature of such approaches that certain tradeoffs are made with regard to detail and while specific external cost factors are provided for air, bus, car and train, no such factor is provided for shipping. However, the recommendation is to use the country specific cost factor which are available for different areas.

As for the external cost factors, it must be noted that only data for $PM_{2.5}$, PM_{10}, SO_2 and volatile organic compounds are considered. It can be argued that limiting oneself to only those pollutants might lead to a more accurate estimate for said pollutants. Still, when comparing aggregated estimates from HEATCO with the results from other methodologies it has to be taken into account that the HEATCO estimates are only based on those four pollutants.

HEATCO has never been used in the context of shipping. This is likely related to the fact that no external cost factors are provided for shipping. Tichavska and Tovar (2015) argue that the cost factors for street traffic are not appropriate to use in the context of shipping as the exhaust gases from the funnel of a ship are released at a higher altitude than the exhaust gases from a car or bus. Tzannatos (2010a,b) argues that the cost factors from BeTa are more appropriate as they are specific to the activity of shipping. Castells et al. (2014) and Maragkogianni and Papaefthimiou (2015) bring forward the argument that there are more recent and updated cost factors than the ones of HEATCO that should be used.

In the here presented study, the arguments of the aforementioned authors are followed and the external cost factors of HEATCO will not be applied.

(4) The New Energy Externalities Development for Sustainability (NEEDS) methodology was initially intended to calculate the “the full (i.e. internal + external) costs of energy technologies” (Korzhenevych et al., 2014). In fact, the use of NEEDS for other emission sources such as shipping was not on the agenda when NEEDS was designed.

However, due to the fact that it covers all major pollutants in all EU member states and their related externalities, it is all but surprising that the provided figures are widely used in other contexts, including maritime transport in general and ports in particular. It is often referred to as “the most updated methodology for calculating external costs of maritime transport" (Nunes et al., 2019) and was for example applied by Maragkogianni and Papaefthimiou (2015) and Tichavska and Tovar (2015).

While NEEDS does provide marginal air pollution cost factors for a variety of sea regions, the categories of vessels that are being covered is limited. Korzhenevych et al. (2014) explained this with a lack of comprehensive data. More specifically, no cost factors are available for Ro-Ro vessels, container vessels, refrigerated vessels, cruise vessels and passenger ferries. Given the structure of vessels calling the ports under study, NEEDS is deemed to be the less suitable for the study conducted here.

The here presented literature review has shown that there is several conducted research applying a wide variety of methodological approaches. To the best of the knowledge of the authors, this is the first paper to compare four ports and provide granular information about ship types and seasonality. Furthermore, eco-efficiency indicators are introduced that might allow to introduce tariffs that are based on said eco-efficiency indicators and vessel types.

3. Material and Methodology

The here presented work extends the work of Spengler and Tovar (2021). While Spengler and Tovar (2021) focused on providing a Spain wide overview of external costs, they offered limited insights into a temporal dimension as well as external costs depending on the type of vessel which will be presented in section 4 of this document. External costs will be computed for vessels at berth.

Figure 1 depicts data sources, processing as well as the obtained results. Emissions of a given pollutant are calculated as a product of the auxiliary engine power in kilowatt, the time in hours and the emission factor for the respective pollutant in tons per kilowatt hour. For estimating the auxiliary engine power, the 3rd International Maritime Organization (IMO) Study on Greenhouse gases (GHG) (Smith et al., 2015) is followed. For obtaining the time, data from the Automatic Identification System (AIS), data on port calls as well as data on the location of berths was used. The emission factor was computed following the methodology of the European Environment Agency (EEA) and the US Environmental Protection Agency (EPA) in the years 2013 and 2010 respectively. This was done under the assumption that the auxiliary engines are of the type “medium speed diesel”, that they are achieving Tier II in terms of NO_x and that they are running on Marine Diesel Oil (MDO)/Marine Gasoil (MGO).

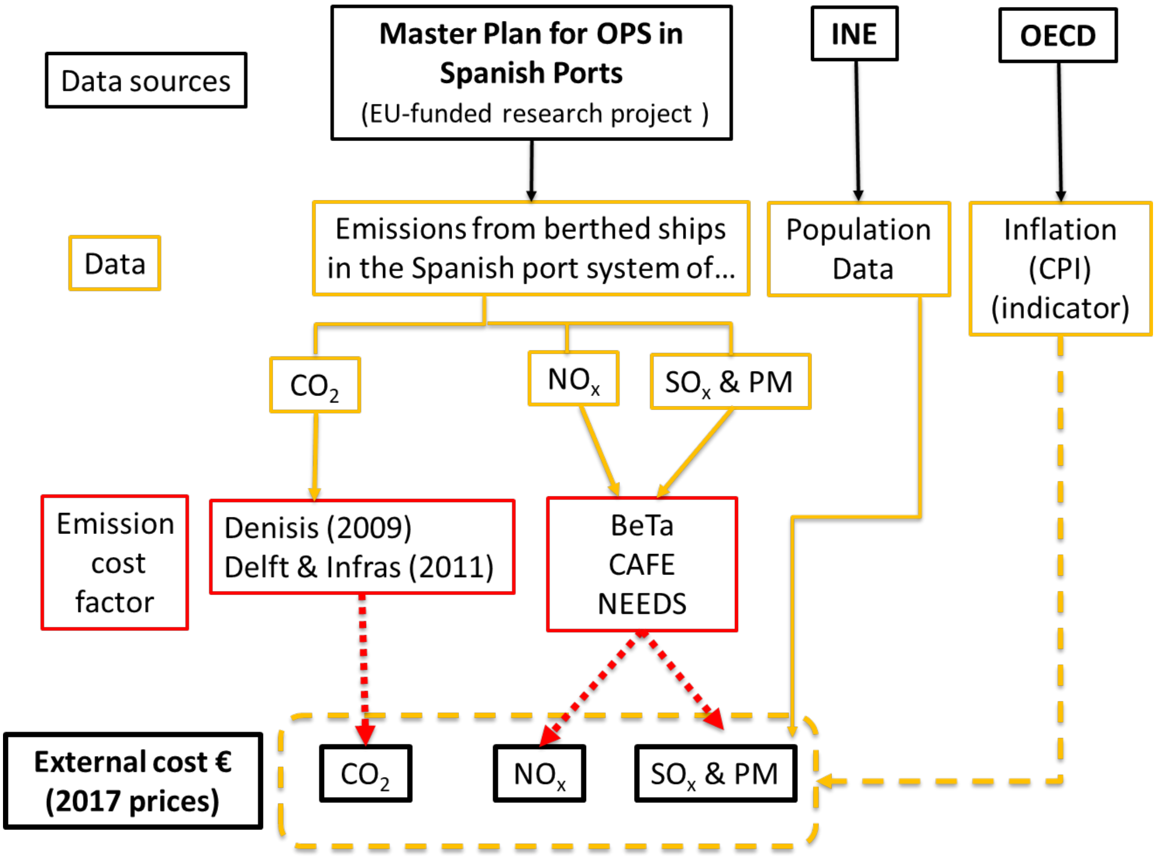


Fig. 1: Flow Chart of Methodology

Source: Authors

Population data for the port cities under study were obtained from the Spanish Instituto Nacional de Estadística (INE).

The emissions occurring during hotelling for , which serve as a basis for the calculations for external costs are estimated based on Equation 1. The emissions E for the pollutant i are obtained in tons. AE is the auxiliary engine power in kilowatt obtained as described above. The time t is obtained from the AIS data and calculated in hours and FE is the respective emission factor for the pollutant i in tons per kilowatt-hour. Equation 1: Formula for estimating emissions

$$E_i = AE \cdot t \cdot FE_i$$

For adjusting the prices for the year 2017, the Consumer Price Index (CPI) for EU28 (OECD, 2019) was utilized.

The data used were obtained through the On-Shore Power Supply (OPS) Master Plan. All member states of the European Union are required to develop policy frameworks to support alternative fuels for sustainable mobility as decided in Directive 2014/94/EU. The Spanish government introduced the National Action Framework for the development of infrastructure for the use of alternative fuels. The OPS Master Plan[12] is part of that action framework.

The following elaborations will focus on the four ports which were the first to become involved in the OPS project which is why they were studied more deeply than the others: Tenerife, Las Palmas de Gran Canaria, Palma de Mallorca and Pasaia. The following subsections will provide the necessary insight into the most important aspects of those ports.

Table 2.1 depicts the mooring hours as well as the emissions of the aforementioned ports.

Table 2.1: Emissions and operative time from vessels at berth (July 2017-June 2018)

Port	**Mooring (hours)**	**NO_X (Tons)**	**SO_X (Tons)**	**PM_{10} (Tons)**	**$PM_{2.5}$ (Tons)**	**CO (Tons)**	**CO_2 (Tons)**
Las Palmas de Gran Canaria	200000	2060	303	55.80	51.70	158	99900
Palma de Mallorca	30000	60.20	8.37	1.21	1.31	4.04	3000
Pasaia	40000	64.50	9.78	1.89	1.73	5.04	3220
Tenerife	70000	693	102	18.50	16.90	54.20	34000

Source: Authors

The port of Las Palmas de Gran Canaria lies in direct vicinity of Las Palmas de Gran Canaria, which has roughly 380000 inhabitants. The port is of significant importance due to its geographic location in the Atlantic between Europe and Latin America. The port is

---

[12] For further information about the OPS Master plan, please refer to http://poweratberth.eu/?lang=en

connected to more than 180 other ports in the world (Port Authority of Las Palmas de Gran Canaria, 2018).

The port is of particular importance as a bunkering port. In 2017 alone, it supplied vessels with 2330190 tonnes of fuel. Also, the port is working on being able to supply vessels with Liquified Natural Gas (LNG).

In 2017, more than one million containers were handled by the port of Las Palmas de Gran Canaria and more than 674000 cruise passengers were recorded. With regard to the overall cargo quantities, it can be said that more than 23 million tons were moved through the port of Las Palmas de Gran Canaria in 2017 (Port Authority of Las Palmas de Gran Canaria, 2018).

The port of Las Palmas de Gran Canaria publishes annual sustainability reports that includes various eco-efficiency and environmental indicators including such that are related to for example air quality (Autoridad Portuaria de Las Palmas de Gran Canaria, 2018). In addition to that, the port of Las Palmas de Gran Canaria is participating in a number of projects related to ecological innovations, eco-efficiency as well as ballast water treatment. This can be seen as an indication that the port of Las Palmas de Gran Canaria is putting substantial effort into reducing external costs.

Furthermore, Laxe et al. (2017) conducted a study based on the concept of synthetic indexes and found that the port of Las Palmas de Gran Canaria ranks first in the environmental dimension, which is related to aforementioned activities as well as positive results in the area of environmental management.

Also, the port of Las Palmas de Gran Canaria has allocated a tender budget of 2.1 million Euros to the installation of cold ironing facilities in the port. Shore power is to be supplied to ferry vessels with a power demand of up to 1600 kW (Loyarte, 2019). In the case of Las Palmas de Gran Canaria, Martínez-López et. al. (2021a) estimated a reduction of external costs because of cold ironing for the feeder vessel as well as for the ro-pax vessel by 28% and 11% respectively.

Tenerife is the largest of the Canary Islands with about 200000 people living in Santa Cruz de Tenerife. However, it should be noted that the city of Las Palmas de Gran Canaria has more inhabitants than Santa Cruz de Tenerife which is relevant in the context of external costs as they are related to the number of inhabitants in the direct vicinity of the port. The port is located in the north-east of the island. In terms of traffic, the port of Tenerife facilitates a wide variety of different cargo ranging from liquid and dry bulk cargo over fish to general cargo.

Quantity wise, general cargo, both containerized and non-containerized, accounted for the highest share in throughput with roughly 7.3 million tons in 2017. This is followed by liquid bulk with 5.1 million tons. It should be noted that almost all of the liquid bulk cargo is oil products.

Martínez-López et al. (2021a) analysed potential savings of external costs by means of cold ironing and LNG in short sea shipping. On the basis of one feeder vessel with a considerable amount of reefer containers and one ro-pax vessel, a variety of estimations were made.

They found that, because of connection and disconnection lag times and the way electricity is produced in Tenerife, the use of cold ironing could potentially lead to higher external costs on a per trip basis than using conventional power generation on board of the vessel by means of auxiliary engines.

The port of Tenerife has an environmental code of conduct (Puertos de Tenerife, 2014). However, it should be noted that the document is somewhat dated as it goes back to 2014. While the code of conduct is mostly referencing applicable law and no direct mention is made in the code of conduct of external costs or cold ironing, the port of Tenerife is participating in the OPS Master Plan and has installed cold ironing facilities that could contribute greatly to reducing external costs.

Mallorca is the largest of the Balearic Islands with roughly 400000 inhabitants. Numerous ferry connections are offered from and to Palma de Mallorca. For example, from and to Valencia and Barcelona. Hence, it is not surprising that a total of 925809 ferry passengers were passing through the port in 2017. Also 1673210 cruise passengers were counted in

2017. It is considered an important destination for cruise vessels in the entire Mediterranean Sea area (Rosa-Jiménez, 2018).

In terms of quantities of cargo, it can be said that roughly one million tons of oil products and almost 8.1 million tons of general cargo were moved through the port. With regard to container traffic, a total of 560542 TEU were handled in the port in 2017 (Autoritat Portuària de Balears, 2018).

With reference to the sustainable development goals, the port authority of the Baleares is stressing its commitment to those goals by also being a member of United Nations Global Compact. This approach is clearly somewhat different from the approach of Las Palmas de Gran Canaria as the global development goals can be regarded as rather rough guidance than providing actionable indicators.

In terms of specific actions, it can be noted that the port of Palma de Mallorca has the same tender budget for the installation of cold ironing facilities as the port of Las Palmas de Gran Canaria.

The port of Pasaia is, in contrast to the other ports under study, not located on an island but on the North of Spanish mainland. Consequently, the structure of operations is somewhat different. The number of passengers in 2017 was only 815. Also, the population is the smallest of the four ports under study with only roughly 16000.

In terms of cargo, a strong specialization can be observed towards the steel industry. A total of 48%, or 1.5 million tons, of the cargo handled in 2017 in Pasaia was steel cargo. Also, the automotive industry, with 400000 tons, plays an important role in Pasaia. While Pasaia is an important fishing port in Spain, with only 25987 tons, fish does not play an important role in the overall cargo structure.

The port of Pasaia follows a hands on approach to air quality as a monitoring device for PM_{10} was obtained from the local government of the Basque country and the hosted air quality surveillance network. While this very practical approach to air quality is noteworthy, it should also be taken into account that there is no mention of sustainability related matters, let alone external costs, in the annual report of the port (Pasaia Port, 2018).

Pasaia as well as the other ports in the study is participating in the pilot for OPS Master Plan.

Table 2.2 shows the external cost factors in Euros adjusted for 2017 per ton according to major European bottom-up studies.

Table 2.2: External costs factor (€/Ton). (2017 prices)

Bottom-up studies	**Local**				**Global**	
	NO_X	**SO_X**	**$PM_{2.5}$**	**CO**	**CO_2**	
					Low	**High**
BeTa urban (Spain)	6590	Depend on port city's population (see Table 3)		-	-	-
BeTa rural (Spain)	6590	5188	11076	-	-	-
CAFE rural (Sensitivity ase 1, Spain)	2818	4660	20591	-	-	-
CAFE rural (Sensitivity case 2, Spain)	4118	7153	31429	-	-	-
CAFE rural (Sensitivity case 3, Spain)	5635	9103	40098	-	-	-
CAFE rural (Sensitivity case 4, Spain)	7803	13005	58522	-	-	-
NEEDS (Korzhenevych et al., 2014)	5380	7643	52033[a]; 211603[b]	-	-	-
Denisis (2009)	-	-	-	3.9	-	-
Delft and Infras (2011)	-	-	-	-	27.5	160.6

Note: a = value for Pasaia. b = value for the other three ports
Source: Authors

While only BeTa is used in further elaborations (when we disagregate by subsector and by month), it is worth comparing the external cost factors that are being used in deeper analysis to the ones that are not.

The external cost factors for NO_X applied here according to BeTa is 6590 Euro which is higher than the external cost factors of NEEDS and CAFE in the sensitivity cases one to three. In terms of external cost factors for SO_X and $PM_{2.5}$, the external cost factors for BeTa are shown in Table 3 as they depend rightfully on the number of inhabitants that are exposed to the pollutant.

Table 3: Urban external costs factor (€/Ton) following BETA for each port. (2017 prices)

Port	**Inhabitants (2018)**	**SO_X**	**$PM_{2.5}$**
Las Palmas de Gran Canaria	378,517	31,842	175,129
Palma de Mallorca	409,661	34,461	189,538
Pasaia	16,128	1,357	7,462
Santa Cruz de Tenerife	204,856	17,233	94,781

Source: Authors

Table 3 shows the local external cost factors (adjusted for 2017 prices) at berth for each port as well as the number of inhabitants. It is apparent that the four ports under study are vastly different in terms of population. As the external cost factors of SO_X and $PM_{2.5}$ are a function of the number of inhabitants, said external cost factors are also vastly different. Those differences underline the necessity as well as benefit of the here presented study. Without concluding prematurely, it can be stated that the potential benefits of implementing abatement technologies such as cold ironing, will differ hugely between different ports.

External cost factors associated with global effects, mostly attributable to the emission of CO and CO_2, are not considered by BeTa, CAFE or NEEDS. The decision is made to use the external cost factors provided by Denisis (2009) and Delft and Infras (2011) for global external costs as shown in table 2. This is in line with Tichavska and Tovar (2015).

In following BeTa, the external costs associated with emissions from vessels at berth are the sum of urban external costs (related to the port city in question) and rural external costs which depend on the country.

4. Results and Discussion

In the following section the results for the four ports under study will be discussed. Table 4 depicts the estimated external costs (in 2017 prices) for each of the ports under study for the different models and scenarios. It does only include local external cost, as the cost associated with CO_2 does not vary between the different methodological approaches.

Table 4: Estimated local external costs at berth of each port (€). (2017 prices)

Bottom-up studies	**LAS PALMAS DE GRAN CANARIA**	**PALMA DE MALLORCA**	**PASAIA**	**TENERIFE**

	TOTAL	% Var/BeTa	TOTAL	% Var/BeTa	TOTAL	% Var/BeTa	TOTAL	% Var/BeTa
BeTA	5.84E+07	100	1.53E+07	100	9.81E+05	100	1.52E+07	100
BeTA + CAFE SC1	5.15E+07	88	1.35E+07	89	7.67E+05	78	1.28E+07	85
BeTA + CAFE SC2	5.61E+07	96	1.47E+07	96	9.15E+05	93	1.44E+07	95
BeTA + CAFE SC3	6.07E+07	104	1.58E+07	104	1.06E+06	108	1.59E+07	105
BeTA + CAFE SC4	6.84E+07	117	1.78E+07	116	1.31E+06	133	1.85E+07	122
BeTA + CAFE SC_Avg	5.92E+07	101	1.55E+07	101	1.01E+06	103	1.54E+07	102
NEEDS	3.62E+07	62	9.01E+06	59	6.10E+05	62	1.20E+07	79

Source: Authors

Table 4 also shows the variations between the different models, combinations of models and scenarios in percent with BeTa as baseline. The combination of BeTa and CAFE yield results that are between 22% below and 33% above the estimations obtained from only BeTa. When considering the average of CAFE scenarios, the differences only are between 1% and 3%.

NEEDS will not be considered in further elaborations as it is not specific to ports and hence offers only limited insight (Tichavska and Tovar, 2015; Spengler and Tovar, 2021). In addition to that, the findings as presented in Table 4 indicate that NEEDS tends to underestimate in-port shipping emissions which is also in line with the findings of Nunes (2019).

In previous studies (Tichavska and Tovar, 2015) BeTa and CAFE with the average of the scenarios was chosen for further analysis. It was decided to not follow those previous approaches here but to only consider BeTa for further analysis. The reasons for that are as follow: (1) the differences between the approaches are negligible as discussed above. (2) It is aligned with the approach of Spengler and Tovar (2021) which can be considered complementary to the present work. Table 5 shows the combined local costs following BETA and global external costs including both the low and high estimates for CO_2 for the ports under study.

Table 5: Estimated total external costs at berth of each port (€). (2017 prices)

External costs	**LAS PALMAS DE GRAN CANARIA**		**PALMA DE MALLORCA**		**PASAIA**		**TENERIFE**	
Local BeTa	58,398,369	58,398,369	15,267,280	15,267,280	981,218	981,218	15,168,202	15,168,202
Global (CO_2 Low)	2,747,079	-	716,587	-	88,620	-	935,997	-
Global (CO_2 high)	-	16,042,942	-	4,184,865	-	517,539	-	5,466,222

Total (with CO_2 Low)	61,145,448	-	15,983,867	-	1,069,838	-	16,104,199	-
Total (with CO_2 high)	-	74,441,311	-	19,452,145	-	1,498,757	-	20,634,424

Source: Authors

In terms of total external costs, including the high estimation for CO_2, the port of Las Palmas de Gran Canaria has the highest external costs with 74.4 million Euros. Followed by Tenerife with 20 million Euros and Palma de Malllorca with 19.5 million Euros. The port of Pasaia has the lowest total external costs with 1.5 million Euros.

While there are many factors that play a role when one wants to explain those differences, unsurprisingly a key role is the number of inhabitants in the direct vicinity of the port and the amount of ship traffic a port is receiving. Palma de Mallorca has roughly 8% more inhabitants than Las Palmas de Gran Canaria. However, the number of moored hours in Las Palmas de Gran Canaria is, with 200.000 hours, roughly 6.5 times higher than the number of moored hours in Palma de Mallorca.

Palma de Mallorca does have with 30.000 moored hours the lowest number. The external costs that occur in this port are roughly the same as in the port of Tenerife, even though Tenerife has more than twice the number of moored hours. Then again, Palma de Mallorca has roughly twice the number of inhabitants of Tenerife.

While number of moored hours and number of inhabitants can certainly not explain all, they clearly are two determining factors when considering external costs from shipping.

Figures 2, 3, 4 and 5 show the development of external costs by vessel type over time for the Ports of Las Palmas de Gran Canaria, Palma de Mallorca, Tenerife and Pasaia respectively.

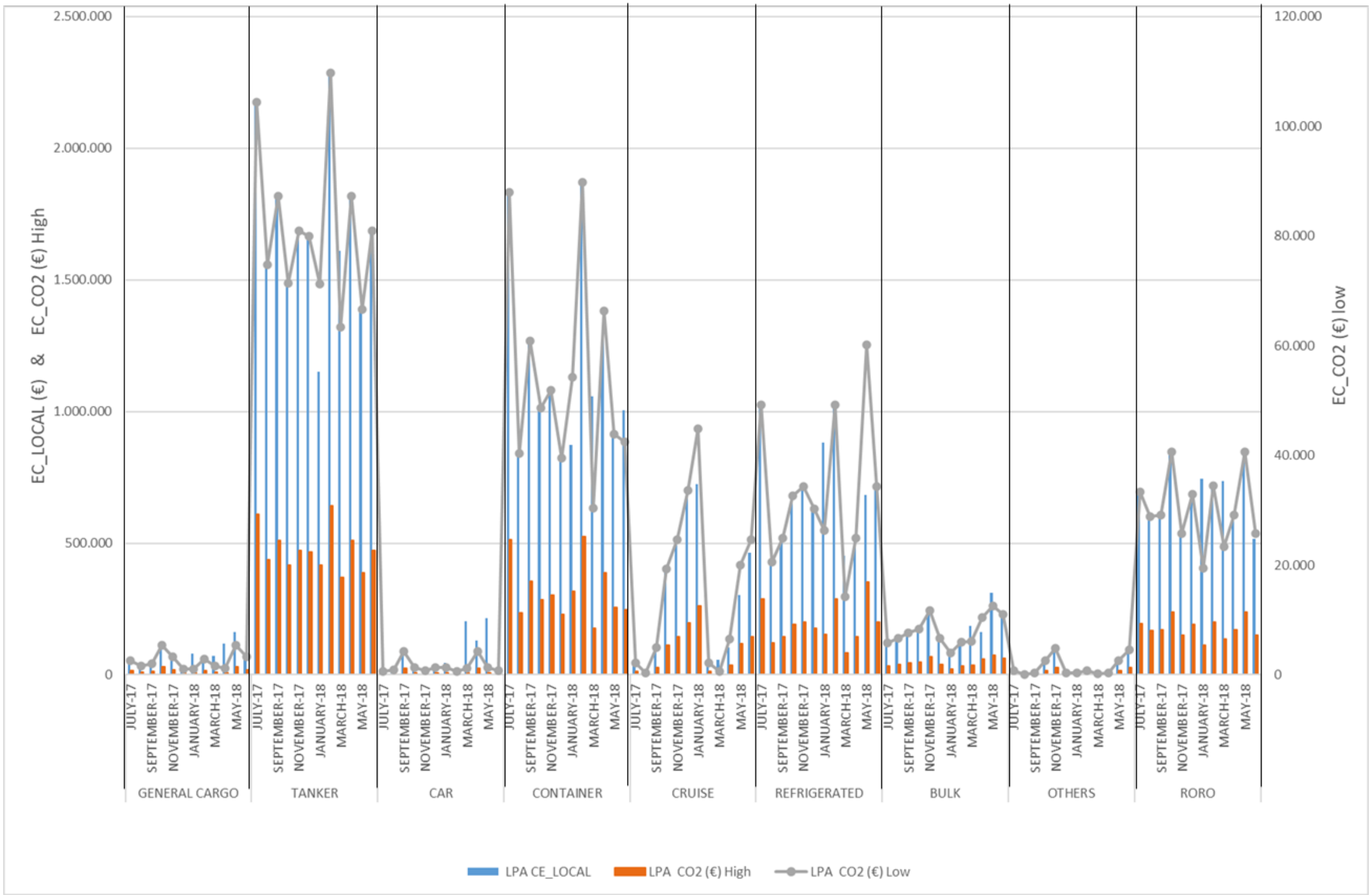


Fig. 2: External monthly costs per vessel type in Las Palmas de Gran Canaria based in BETA (€ 2017). July-17-June 2018

Source: Authors

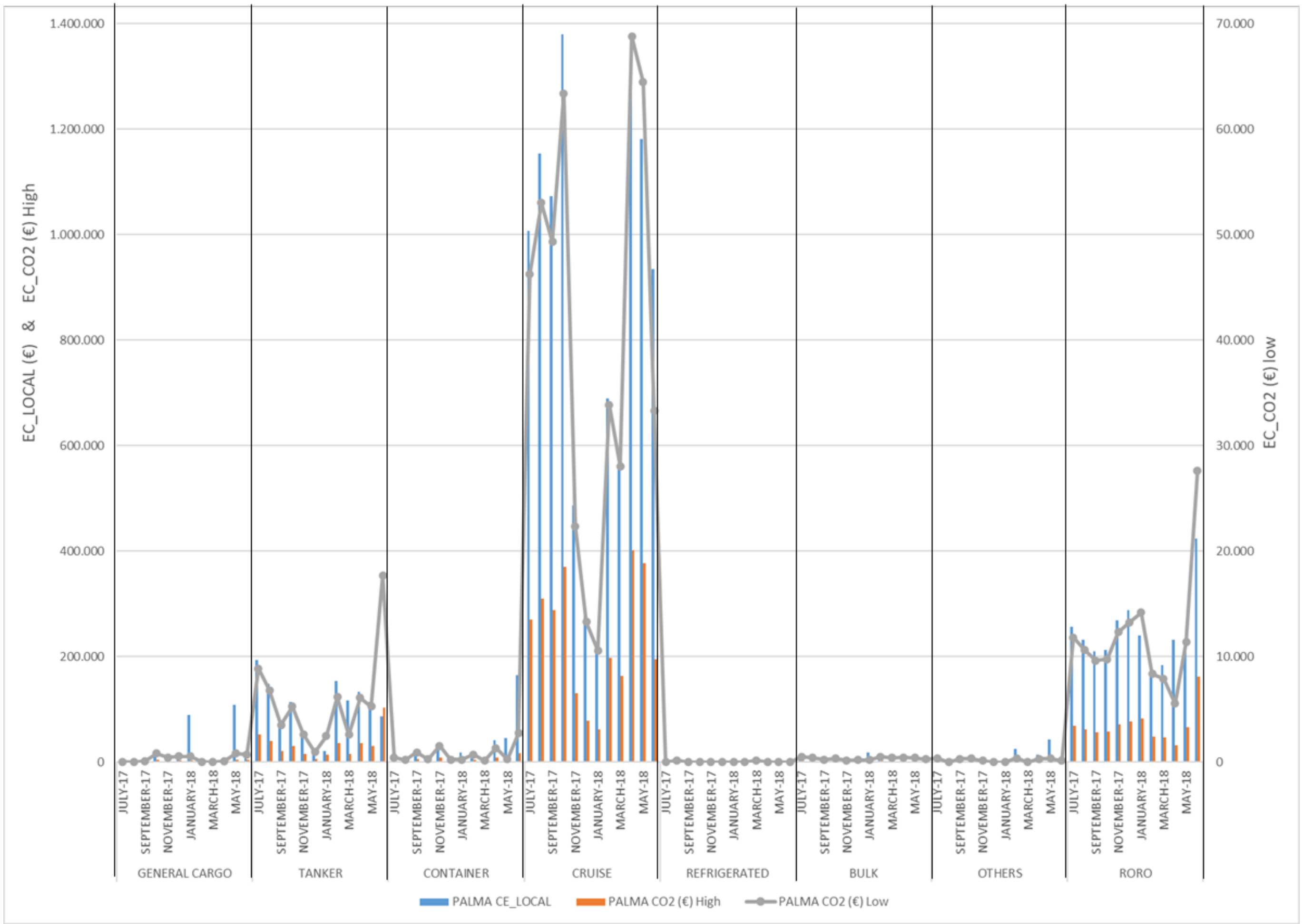


Fig. 3: External monthly costs per vessel type in Palma de Mallorca based in BETA (€ 2017). July-17-June 2018

Source: Authors

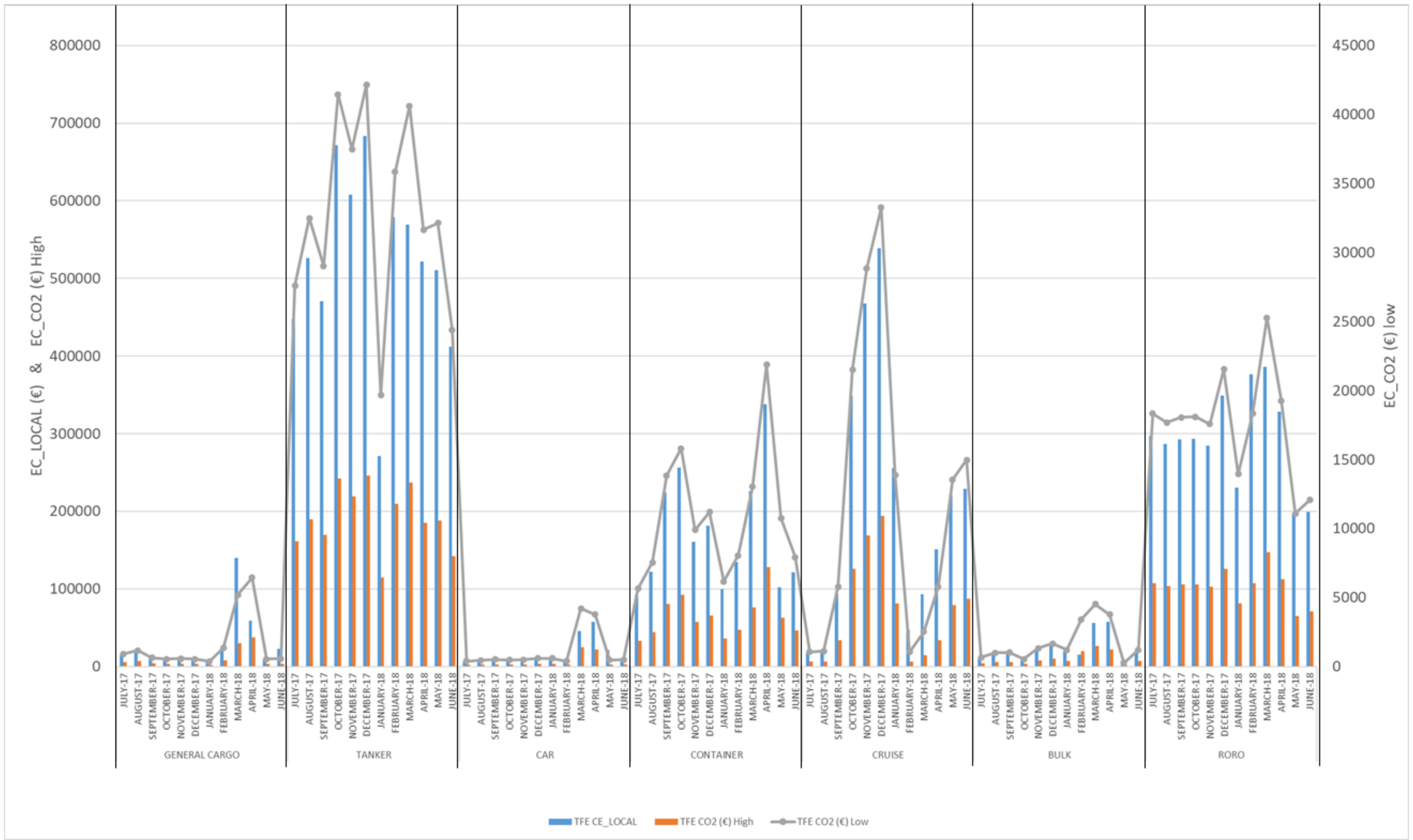


Fig. 4: External monthly costs per vessel type in Tenerife based in BETA (€ 2017). July-17-June 2018

Source: Authors

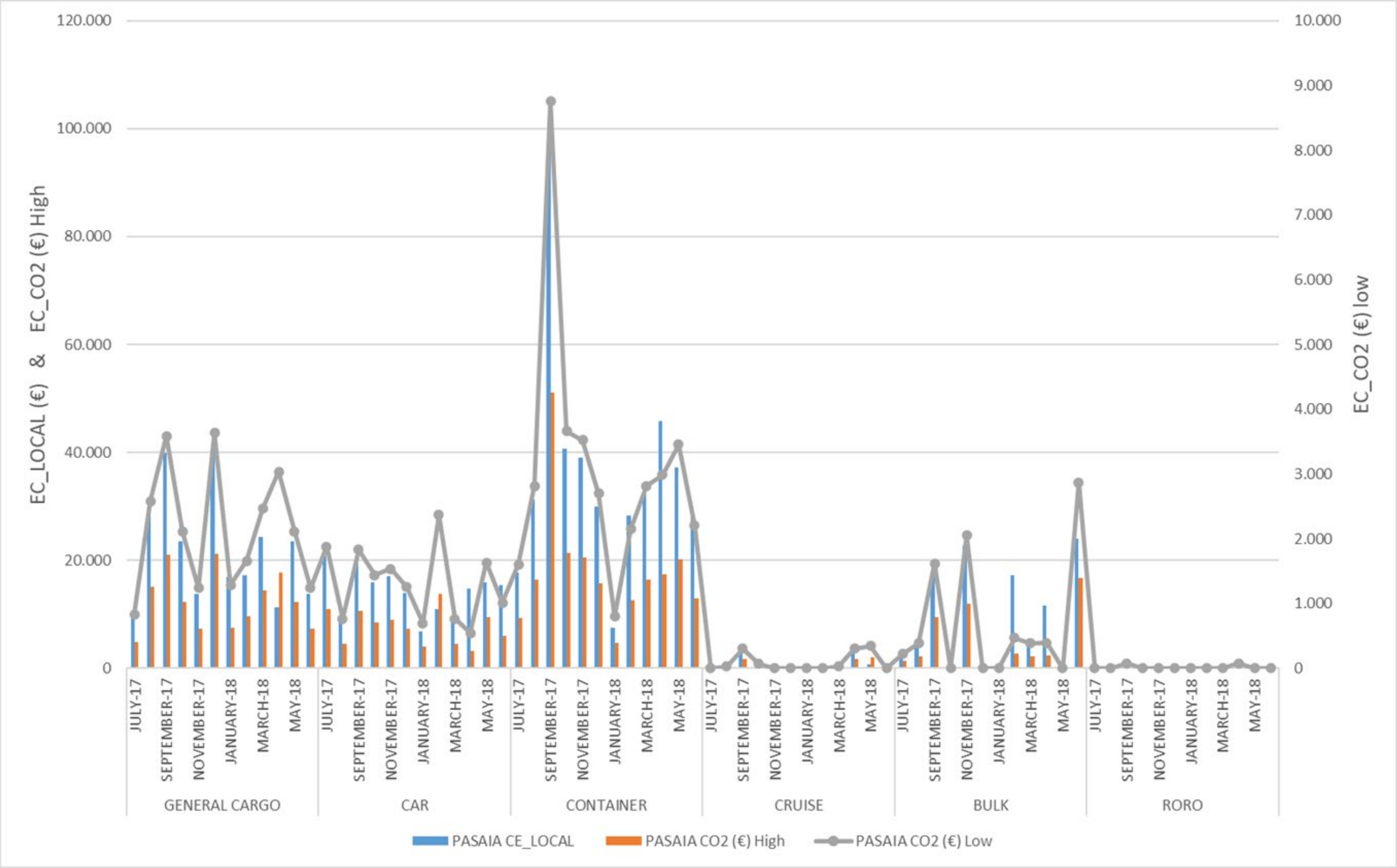


Fig. 5: External monthly costs per vessel type in Pasaia based in BETA (€ 2017). July-17-June 2018

Source: Authors

In all ports, with the exception of Pasaia, a clear seasonality of external costs can be observed with respect to external costs associated with cruise traffic. Pasaia does receive virtually no cruise traffic at all. In the remaining ports the seasonality in cruise traffic is different. While Tenerife and Las Palmas de Gran Canaria have clear peaks in the winter months of the northern hemisphere, the external costs in Palma are much higher in the summer months of the northern hemisphere. This clearly can be attributed to differences in the meteorological conditions on those islands.

In Las Palmas de Gran Canaria and Tenerife, the highest share of external costs can be in most months attributed to liquid bulk traffic. Las Palmas de Gran Canaria is, because of its geographical location, an important port for bunkering for vessels trading between Latin America, Africa and Europe. In Tenerife there is a refinery in the port.

A more or less high but consistent amount of external costs that can be attributed to Ro-Ro vessels can be observed in Las Palmas de Gran Canaria, Palma de Mallorca and Tenerife. Given the nature of ship traffic on islands, that is what is to be expected.

A variety of factors play a role if one is to determine the external cost of a vessel that is calling a port. There clearly are differences between ship types that cannot be explained by the mere number of calls of a given ship type. Some are inarguably related to the average time a given vessel is berthed. Others can be thought to be related to the properties of a given vessel type and the age of the vessel in question. Liquid bulk carriers, for instance, usually are larger in average than container vessels or RoRo vessels. Vessel size, however, can also not explain the differences alone. Refrigerated vessels are generally small as they need to call ports in remote places and there would rarely be enough cargo that would allow for a much bigger vessel. However, even when alongside, refrigerated vessels need to maintain a certain temperature in the cargo hold. This makes it necessary for them to produce a relatively high amount of electricity onboard the vessel.

The vastly different patterns of external costs from different types of vessels make it necessary to look at the matter from a perspective of relative indicators rather than absolute values. The indicators that were chosen are the ones of Euros per hour as well as Euros per vessel call as they are believed to provide the best insight into the difficult patterns that need explaining.

Figure 6 depicts the local external cost per moored hour of different vessel types in different ports and Figure 7 depicts the external costs associated with port calls of different vessel types in the ports under study. It is obvious that the external costs differ substantially between those indicators but also between ports and types of vessels.

Figure 6 and Figure 7 have to be viewed as being complementary. This becomes apparent when considering, for example, the external cost of reefer vessels. In Las Palmas de Gran Canaria the associated external cost per mooring hour of reefer vessels is relatively low when compared to Palma. However, when the external cost per port call is considered, the picture is the exact opposite: Reefer vessels have the highest external cost per port call in the port of Las Palmas de Gran Canaria while the external costs of port calls of reefer vessels is relatively low in Palma de Mallorca. A similar observation can be made for cruise vessels.

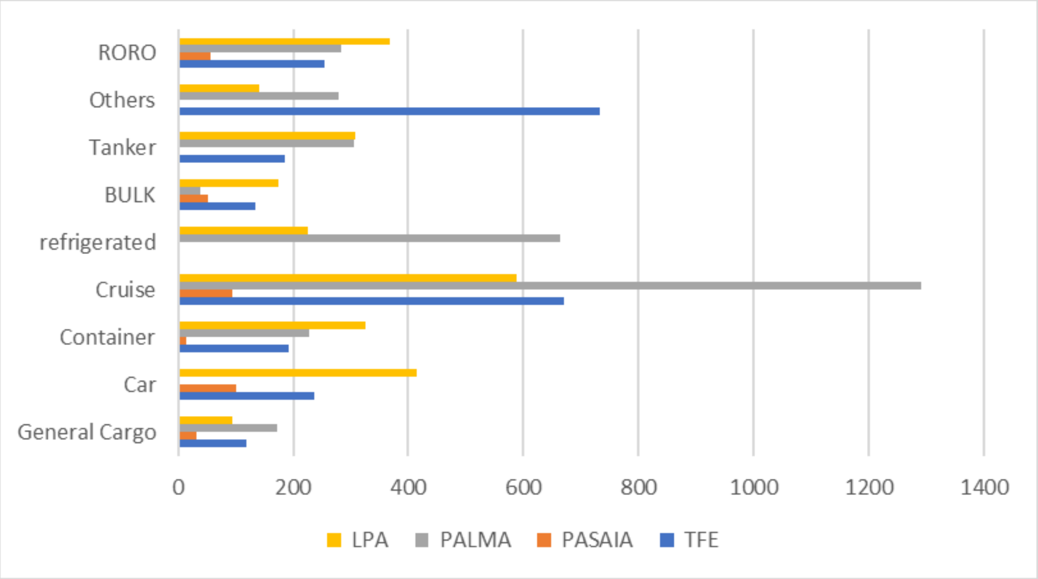


Fig. 6: Local External Costs per moored hour

Source: Authors

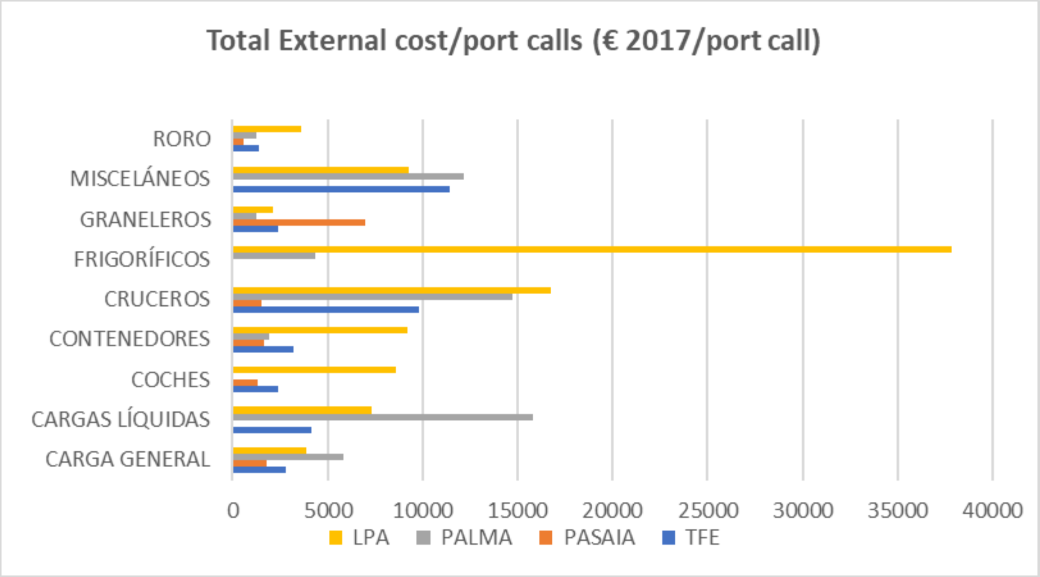


Fig. 7: Total External Cost per port call

Source: Authors

The reason for those differences can lie in a number of factors reaching from specific vessel properties to the mere duration of a port stay. By way of example, if a comparably small (and there with relatively old) refrigerated vessel calls the port of Palma de Mallorca, it is likely that this vessel will have high external costs for the time it is moored. However, the cargo operations will not take the same time as with a comparably large vessel. The opposite also holds true: If a modern, efficient large vessel calls, by way of example the port of Las Palmas de Gran Canaria, the external costs per hour will be relatively low. However, the vessel is likely to stay longer and the external costs for this port call will be higher in total.

Interestingly, efficiencies of scale are not substantially observable in the external costs per hour. Container vessels are a good example for this. Intuition would suggest that external costs per hour are less in ports that are specialized on a certain vessel type. Las Palmas de Gran Canaria received 601 calls from container vessels, more than any other vessel type. In Palma de Mallorca, only 22 calls from container vessels could be observed. However, the external costs are 337 euro and 122 euro respectively. In fact, Las Palmas de Gran

Canaria is the port with the highest number of vessel calls from container vessels and also the port with the highest external costs.

Reasons for those counterintuitive figures are likely to lie within the differences in the same category of vessels. The size[13] of container vessels can range from below 100 metres to almost 400 metres. Therewith come great differences in generators that are in the end directly linked to the external costs for moored vessels.

5. Conclusion and further research

In recent years, air emissions and the negative effects derived from the growth of shipping has increasingly raised concern. Emission inventories and its economic valuation as external costs are necessary to properly assess mitigation strategies, voluntary programs and an effective policy design within national and international contexts.

This paper contributes to the literature by estimating the external costs of in-port shipping emissions (GHG and exhausts emissions commonly related to local detriments on air quality: NO_x. SO_x, CO and PM) released by operative vessels at berth in four Spanish ports (Palma de Mallorca, Tenerife, Las Palmas de Gran Canaria and Pasaia) during 2017-2018.

The four port under study are quite heterogeneous in terms of cargo specialisation and size, have different traffic profiles and are located in cities of different population. The external cost estimated might be correlated with these different characteristics and thus offer a whole picture of different externality costs derived from ships. The differences also facilitate the comparison of the responsibility among the different shipping sectors in order to better know the potential benefits of implementing abatement technologies, such as cold ironing, will differ hugely between different ports.

The presented results firstly point towards the great role the local effects of emissions in terms of external costs have on the cities and regions in the direct vicinity of a port. It was

---

[13] The gross register tonnage is important as well. In fact, there is a high correlation of gross register tonnage and length. This is almost perfect in the case of container vessels.

shown that the external costs in a port is linked to the vessel type in question. However, it was also discussed that the findings leave room for interpretation because there can also be great differences within one vessel type.

Furthermore, the great potential for abatement technologies such as cold ironing is underlined by the findings in this work. It is now possible to assess to what extent such abatement technologies make sense and point towards the need of assessing the potential in each individual port per vessel type as the differences are apparent.

A remaining challenge of cold ironing is how the retrofitting of vessels could take place. Martínez-López (2021b) offer a promising approach where environmental charges are based on a variety of factors that could incentivize the retrofitting of short sea shipping vessels with cold ironing facilities. However, it should be noted that the effect will depend to a wide extent on how the on-shore electricity is produced as discussed in the introduction.

One limitation of the here presented approach is that it intrinsically limited to externalities that can be attributed to vessel traffic. Depending on the equipment deployed within a given port, a substantial share of emissions that might be contributing to externalities has not been within the scope of this document. The same can be said for externalities that arise when certain cargo is handled such as for example solid bulk cargo.

A further limitation of this document lies in the reliance on the deployed methodologies. If those methodologies will be proven to be inaccurate, the here presented findings will consequently also have to be regarded as less valid. Furthermore, the external cost factors used in this document depend on value of life estimations. These estimations are often subject to criticism from both a moral as well as methodological point of view. In absence of a more favorable approach, the potential short comings are not assumed to outweigh the benefits of the here presented findings.

Notwithstanding the fact that estimating emissions as well as external costs are of key importance regardless of a pandemic, it should be recognised that the substantial changes in cruise vessels provide a unique research opportunity. As it was hinted at in the introduction, considerably less traffic can be expected for 2021 in the cruise industry and potentially also 2022 depending on how the dynamic COVID-19 situation will evolve. Albeit a disastrous event, the outbreak of COVID-19 opens up a chance to investigate how external costs are evolving in a world with close to no cruise shipping. While close to no impact can be observed on cargo traffic, multiple scenarios are feasible where this might change in the future.

It remains to be seen how the industry will develop in the upcoming years and how future research possibilities might evolve.

A more technical challenge that needs to be overcome is the one of different alternating current frequencies between the ship and the shore grid. Most vessels operate with an AC frequency of 60 Hz while the power grid in European countries is operated with 50 Hz. The conversion from 50 to 60 Hz usually happens on the shore side and is associated with additional costs. Also, the matter of standardization of connectors must not be underestimated in complexity as well as regulatory constraints imposed by for example Safety of Life at Sea (SOLAS). The biggest challenge however can be seen to lie within the (retro) fitting of vessels with cold ironing technology that can be a significant cost factor. The here provided findings may help to determine for what vessels and ports, cold ironing might yield the highest benefits.

In addition to analysing the likely impact of COVID-19, it also remains to be analysed why the differences within the vessel types exist. This can help to also further assess the potential benefits cold ironing could have. Further developments from institutions like the IMO and the EU commission as well as a potential shift to renewable resources might also mandate further research in this area.

Acknowledgements

Financial assistance for this work was provided by the EU-funded research project Master Plan for OPS in Spanish Ports (Agreement No. INEA/CEF/TRAN/M2015/1128893).

6. References

Adamo, F., Andria, G., Cavone, G., De Capua, C., Lanzolla, A.M.L., Morello, R., Spadavecchia, M., 2014. Estimation of ship emissions in the port of Taranto. Measurement 47, 982–988. doi: 10.1016/j.measurement.2013.09.012.

Autoridad Portuaria de Las Palmas (2018). Memoria Sostenibilidad. Available at: http://www.palmasport.es/wp-content/uploads/2019/11/Memoria2018.pdf

Berechman, J., Tseng, P.H., 2012. Estimating the environmental costs of port related emissions: the case of Kaohsiung. Transp. Res. Part D 17 (1), 35–38.

Castells, S.M., Usabiaga, S.J.J., Martínez, D.O.F.X., 2014. Manoeuvring and hotelling external costs: enough for alternative energy sources? Marit. Policy Manage. 41 (1), 42–60

Chatzinikolau, S.; Stylianos, d.; Oikonomou, D; Ventikos, N. 2015. Health externalities of ship air pollution at port – Piraeus port case study. Transp. Res. Part D 40, 155-165.

Delft, C.E., Infras, F.I., 2011. External Costs of Transport in Europe. Update Study for 2008. Commissioned by: International Union of Railways UIC. Delft, CE Delft, September, 2011.

Denisis, A. 2009. An Economic Feasibility Study of Short Sea Shipping Including the Estimation of Externalities with Fuzzy Logic (Doctoral dissertation).

Ito, H., Hanaoka, S., & Kawasaki, T. 2020. The cruise industry and the COVID-19 outbreak. Transportation Research Interdisciplinary Perspectives, 5, 100136.

Korzhenevych, A., Dehnen, N., Bröcker, J., Holtkamp, M., Meier, H., Gibson, G., ... & Cox, V. 2014. Update of the handbook on external costs of transport: final report for the European Commission: DG-MOVE.

Laxe, F. G., Bermúdez, F. M., Palmero, F. M., & Novo-Corti, I. 2017. Assessment of port sustainability through synthetic indexes. Application to the Spanish case. Marine pollution bulletin, 119(1), 220-225.

Loyarte, L. 2019, Puerto de Las Palmas de Gran Canaria abre convocatoria para proyecto de conexión eléctrica a tierra para ferris. Logi News. Available at: https://noticiaslogisticaytransporte.com/logistica/25/09/2019/puerto-de-las-palmas-abre-convocatoria-para-proyecto-de-conexion-electrica-a-tierra-para-ferris/141669.html

Martínez-López, A., Romero, A., & Orosa, J. A. 2021a. Assessment of Cold Ironing and LNG as Mitigation Tools of Short Sea Shipping Emissions in Port: A Spanish Case Study. Applied Sciences, 11(5), 2050.

Maragkogianni, A., & Papaefthimiou, S. 2015. Evaluating the social cost of cruise ships air emissions in major ports of Greece. Transportation Research Part D: Transport and Environment, 36, 10-17.

Martínez-López, A., Romero-Filgueira, A., & Chica, M. 2021b. Specific environmental charges to boost Cold Ironing use in the European Short Sea Shipping. Transportation Research Part D: Transport and Environment, 94, 102775.

IPCC, 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty [Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.)]. https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf. Accessed date: 1 August 2021.

Nunes, R. A., Alvim-Ferraz, M. C. M., Martins, F. G., & Sousa, S. I. 2019. Environmental and social valuation of shipping emissions on four ports of Portugal. Journal of environmental management, 235, 62-69.

McArthur, D.P., Osland, L., 2013. Ships in a city harbour: an economic valuation of atmospheric emissions. Transp. Res. Part D 21, 47–52

Notteboom, T. E., & Haralambides, H. E. 2020. Port management and governance in a post-COVID-19 era: quo vadis?.

Pasaia Port 2018. Memoria. Available at: http://www.pasaiaport.eus/images/2018_REPORT.pdf

Puertos de Tenerife 2014. Codigo de Conducta Ambiental. Available at: https://www.puertosdetenerife.org/wp-content/uploads/2019/10/C%C3%B3digo-de-Conducta-Ambiental-de-Puertos-de-Tenerife.pdf

Rosa-Jiménez, C., Perea-Medina, B., Andrade, M. J., & Nebot, N. 2018. An examination of the territorial imbalance of the cruising activity in the main Mediterranean port destinations: Effects on sustainable transport. Journal of Transport Geography, 68, 94-101.

Sciberras, E.A., Zahawi, B., Atkinson, D.J., 2015. Electrical characteristics of cold ironing energy supply for berthed ships. Transport. Res. Transport Environ. 39, 31–43. doi: 10.1016/j.trd.2015.05.007.

Sorte, S., Rodrigues, V., Borrego, C. Monteiro, A. 2020. Impact of harbour activities on local air quality: A review. Environmental Pollution, 257, 113542.

Spengler, T., & Tovar, B. 2021. Potential of cold-ironing for the reduction of externalities from in-port shipping emissions: The state-owned Spanish port system case. Journal of Environmental Management, 279, 111807.

Tichavska, M., & Tovar, B. 2015. Environmental cost and eco-efficiency from vessel emissions in Las Palmas Port. Transportation Research Part E: Logistics and Transportation Review, 83, 126-140.

Tichavska, M., & Tovar, B., 2017. External costs from vessel emissions at port: a review of the methodological and empirical state of the art. Transport Reviews, 37(3), pp. 383-402.

Tovar, B., & Tichavska, M. 2019. Environmental cost and eco-efficiency from vessel emissions under diverse SOx regulatory frameworks: A special focus on passenger port hubs. Transportation Research Part D: Transport and Environment, 69, 1-12.

Tovar, B., & Wall, A. 2019. Environmental efficiency for a cross-section of Spanish port authorities. Transportation Research Part D: Transport and Environment, 75, 170–178. doi: 10.1016/j.trd.2019.08.024

Tovar, B., & Wall, A. 2021. The external costs of port activity for port cities: An environmental efficiency analysis of Spanish ports, International Journal of Sustainable Transportation, 1-13. doi: 10.1080/15568318.2021.1943074

Tzannatos, E., 2010a. Ship emissions and their externalities for the port of Piraeus Greece. Atmos. Environ. 44 (3), 400–407.

Tzannatos, E., 2010b. Ship emissions and their externalities for Greece. Atmos. Environ. 44 (18), 2194–2202.

Viana, M., Rizza, V., Tobías, A., Carr, E., Corbett, J., Sofiev, M., Karanasiou, A., Buonanno, G., Fann, N., 2020. Estimated health impacts from maritime transport in the Mediterranean region and benefits from the use of cleaner fuels. Environment International, 138, 105670.

Zis, T.P., 2019. Prospects of cold ironing as an emissions reduction option. Transportation Research Part A, 119, 82-95. doi: 10.1016/j.tra.2018.11.003.

Zis, T., North, R.J., Angeloudis, P., Ochieng, W.Y., Bell, M.G.H., 2014. Evaluation of cold ironing and speed reduction policies to reduce ship emissions near and at ports. Maritime Economic & Logistic, 16, 371-398. doi: 10.1057/mel.2014.6.

Conclusión

Resumiendo, esta tesis contribuye al corpus bibliográfico existente de varias maneras:

Se demostró que el análisis de la eficiencia y la productividad de las terminales portuarias de contenedores basado en el Análisis Envolvente de Datos (DEA) debería incluir, al menos, una diferenciación del los contnedores manipulados secos y refrigerados, especialmente cuando se comparan terminales de contenedores que tienen porcentajes muy diferentes de estos dos tipos de contenedores.

El Capítulo 1 contribuye además al corpus bibliográfico existente al considerar la energía como un factor productivo específico. No se pudo encontrar la esperada relación significativa entre el volumen de contenedores refrigerados manipulados y el consumo de electricidad en las puntuaciones de eficiencia obtenidas. Esto puede considerarse una indicación de que otras factores productivos si incluidos están estrechamente relacionados con el volumen de contenedores refrigerados manipulados. Una de esas variables puede ser la mano de obra, ya que la manipulación de contenedores refrigerados es un proceso mucho más intensivo en mano de obra que la manipulación de contenedores secos.

La contribución del Capítulo 2 consiste en demostrar que el atractivo y la viabilidad del cold ironing como tecnología de reducción no pueden juzgarse únicamente en función del impacto global de las emisiones del transporte marítimo. La necesidad de tener en cuenta los efectos locales se hace evidente cuando las emisiones de contaminantes que producen efectos locales se traducen a costes externos.

Por otra parte, se demostró que es necesario un análisis refinado y adaptado si se quiere hacer una evaluación sólida de los beneficios potenciales que puede tener el cold ironing en un puerto determinado. Este análisis debería incluir los indicadores de ecoeficiencia coste externo por hora atracada y coste externo por escala de barco.

El Capítulo 3 contribuyó con un análisis granular de los costes externos, teniendo en cuenta los distintos tipos de buques dentro de un puerto. De este modo se puede comprender en profundidad la contribución de cada sector naviero a los costes externos de un puerto.

Además de las contribuciones al corpus bibliográfico existente, los resultados aquí obtenidos pueden tener una serie de implicaciones para las partes interesadas, tanto del sector público como del privado:

Para los operadores mundiales de terminales de contenedores, las implicaciones del capítulo 1 de esta tesis pueden ser que cualquier comparación de la eficiencia de sus terminales debe tener en cuenta la cuota de contenedores refrigerados en sus terminales, lo cual requiere tratar ambos tipos de contenedores como productos diferentes y no utilizar una medida que los agrege.

Además, los operadores de terminales mundiales deberían tener en cuenta las conclusiones del capítulo 1 con respecto a las diversas interrelaciones entre los factores productivos utilizados a la hora de establecer indicadores clave de rendimiento (KPI).

Los capítulos 2 y 3 tienen implicaciones sustanciales para los responsables de la toma de decisiones y, potencialmente, para los reguladores. En primer lugar, se ha demostrado que el cold ironing es una tecnología de reducción muy atractiva cuando se deja de considerar únicamente el impacto global y se reconoce la importancia de los efectos locales y sus costes externos asociados.

Cuando se reconoce que el cold ironing es una tecnología de reducción adecuada, las partes interesadas se enfrentan a dos retos distintos cuando se trata de la inversión o la necesidad de instalaciones de cold ironing: (1) decisiones relativas al puerto en el que se realiza la inversión y (2) decisiones relativas al atracadero en el que se realiza la inversión.

Determinar el puerto con el mayor beneficio potencial es más complicado de lo que podría sugerir la intuición. Atender a los costes externos más elevados por ciudad portuaria no puede considerarse suficiente para orientar una decisión. El Capítulo 2 ha mostrado la necesidad de un análisis que tenga en cuenta los indicadores de ecoeficiencia para poder tomar una decisión acertada.

El Capítulo 3 ha permitido realizar un reparto adecuado de responsabilidades entre los distintos sectores del transporte marítimo. Asimismo, el enfoque metodológico desplegado permite elaborar un ranking para priorizar y orientar las inversiones hacia aquellos puertos y sectores del transporte marítimo en los que cabe esperar un mayor impacto.

Teniendo en cuenta los diferentes requisitos operativos de los distintos tipos de buques, lo más probable es que las orientaciones con respecto al sector naviero también impliquen orientaciones con respecto a un puesto de atraque.

Aunque aquí se ofrecen muchas ideas sobre muchos aspectos diferentes de la sostenibilidad y el rendimiento en los puertos, también se revela el potencial de futuras investigaciones.

El capítulo 1 indica que sería deseable construir futuros modelos con datos más estrechamente relacionados con algunos de los objetivos económicos de una terminal. Aunque este capítulo se ha dedicado únicamente a la eficiencia técnica, la cuestión de la eficiencia económica reviste un gran interés para futuras investigaciones.

En el Capítulo 2 se demostró que existen claras diferencias cuando se consideran los costes externos en el contexto de los indicadores de ecoeficiencia. La investigación futura debería abordar cómo llegan a existir esas diferencias. Uno de los posibles aspectos que debería investigarse más a fondo es el tipo de buque. Es decir, si se trata de un buque portacontenedores, granelero, de carga rodada o de crucero. Es de esperar que esto desempeñe un papel importante en lo que respecta a los indicadores de ecoeficiencia introducidos.

El capítulo 3 indica que el potencial para seguir investigando reside en analizar las razones por las que existen las diferencias dentro de los tipos de buques. De este modo, también se pueden evaluar mejor las posibles ventajas que podría tener el cold ironing. Otros avances de instituciones como la OMI y la Comisión Europea, así como un posible cambio hacia los recursos renovables, también podrían obligar a seguir investigando en este ámbito.

Conclusion

In summary, this thesis contributes to the existing body of literature in a number of ways:

It was shown, that port efficiency and productivity analysis based on data envelopment analysis (DEA) should at least include an differentiation of outputs with respect to dry and reefer containers when comparisons of container terminals are made that have vastly different shares of refrigerated containers.

Chapter 1 further contributes to the existing body of literature by considering energy as input variables. The expected significant relationship between the volume of reefer container throughput and electricity consumption could not be found in the obtained efficiency scores. This can be seen as an indication that other input variables are closely related to the volume of handled reefer containers. One such variable can be thought to be labour as handling reefer containers is a far more labour intensive process than handling dry containers.

Chapter 2 contribution lies in showing that the attractiveness and viability of cold ironing as an abatement technology cannot be judged solely on the global impact of shipping emissions. The need to take local effects into account becomes apparent when said local effects are considered as external costs.

Furthermore, it was shown that a refined and tailored analysis is necessary if one is to make a statement about the potential benefits cold ironing can have at a given port. This analysis should include the eco-efficiency indicators external cost per hour berthed and external cost per ship call.

Chapter 3 contributed by a granular analysis of external costs, taking into consideration the different vessel types within a port. This allows for an in-depth understanding of the contribution of each shipping sector to the external costs in a port.

In addition to the contributions to the existing body of literature, a number of implications for stakeholders from the public as well as private sector can be derived from the here obtained results:

For global container terminal operators, implications from chapter 1 of this thesis can be thought to be that any comparison of productivity of their terminals need to take into consideration the share of refrigerated containers in their terminals.

Furthermore, findings from chapter 1 with respect to various interlinkages of input variables should be considered by global terminal operators when setting key performance indicators (KPI).

For decision makers and potentially regulators chapter 2 and 3 have substantial implications. Firstly, it was shown that cold ironing is a very attractive abatement technology when the focus is shifted from only considering the global impact but also recognizing the importance of local effects and consider them as external costs.

When cold ironing is recognized as a suitable abatement technology, stakeholders are faced with two distinct challenges when it comes to the investment into or the requirement of cold ironing facilities: (1) decisions pertaining to the port where the investment is made and (2) decisions pertaining to the berth where the investment is made.

Finding the port with the highest potential benefit is more complicated than one's intuition might suggest. Looking at highest external costs per city cannot be thought to be enough to guide a decision. Chapter 2 has shown the need for an analysis that takes into consideration eco-efficiency indicators in order to be able to make a sound decision.

Chapter 3 has made it possible that a proper allocation of responsibilities among the different shipping sectors can be carried out. Also, the deployed methodological approach allows for building a ranking to prioritize and guide investment to those ports and shipping sectors where the greatest impact can be expected.

Given the different operational requirements of different vessel types, guidance with respect to the shipping sector will most likely also imply guidance with respect to a berth.

While many insights into many different aspects of sustainability and performance in ports are offered here, also potential for further research is revealed.

Chapter 1 suggests it would be desirable to construct future models with data that are more closely related to some of the economic objectives of a terminal. While the focus of this chapter was merely technical efficiency, the matter of economic efficiency is of significant interest for future investigation.

In Chapter 2 it was shown that there are clear differences when external costs are considered in the context of eco-efficiency indicators. Future research should address how those differences come to exist. One potential aspect that should be further investigated is the vessel type. That is to say, whether it is a container, bulk, Roll-On Roll-Off or cruise vessel. It is expected that this plays a major role when it comes to the introduced eco-efficiency indicators.

Chapter 3 indicates that potential for further research lies in analysing why the differences within the vessel types exist. This can help to also further assess the potential benefits cold ironing could have. Further developments from institutions like the IMO and the EU commission as well as a potential shift to renewable resources might also mandate further research in this area.