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Research article

Cost-benefit assessment of shore side electricity: An Irish perspective

Ketan Gore [*], Patrick Rigot-Müller, Joseph Coughlan

School of Business, Maynooth University, Maynooth, W23 WK26, Ireland

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ABSTRACT

This study, based on 2019 data, investigates the cost-effectiveness of Shore Side Electricity (SSE) adoption utilising the existing and future (2030) Irish energy mix, while considering different levels of adoption across six scenarios, incorporating both “port-side” and “ship-side” private costs alongside the benefits from reduced external costs and avoided Auxiliary Engine (AE) fuel costs. Passenger ships calling to the two most populated Irish port cities of Dublin and Belfast were selected as the case study, owing to the significance of such ports and ship types in the Irish maritime economy. For the existing Irish energy mix, the most optimal solution among the discussed scenarios was that of switching the top 10 most frequent passenger ship callers in Dublin and Belfast to SSE, as it reflected the highest Net Present Values (NPV) of €34.06 million and €15.44 million, respectively. The future (year 2030) SSE supply is expected to be “cleaner” due to an increase in the uptake of renewable energy sources, which will further boost the obtained NPVs by 50%. A combination of public funding (by 50%), increment in supplied electricity price by 8.62% (for Dublin) and 10.01% (for Belfast) and an annual ticket price supplement (per passenger seat) by €0.03 (for Dublin) and €0.04 (for Belfast), can create a business case for the identified optimal scenario.

1. Introduction

When at berth, ships use their Auxiliary Engines (AE) to generate electricity for essential ‘hotelling’ services which include communications, lighting, and other onboard equipment (Tzannatos, 2010; Winkel et al., 2016). In port cities, emissions from these ship-based activities are identified as a significant source of air pollution (Castells Sanabra et al., 2014). It has been acknowledged that approximately 450 different types of pollutants are emitted by marine engines as a part of their internal combustion process, including oxides of sulphur (mainly sulphur dioxide (SO_2)), nitrogen oxides (NO_x), particulate matter (PM) and greenhouse gases (mostly carbon dioxide (CO_2)) (Alver et al., 2018). These pollutants have important implications for not only the environment, but also for the local population residing near the coastline (Tzannatos, 2010).

Shore Side Electricity (SSE) is seen as an alternative to reduce the emissions of AEs and thus ameliorate the negative effects of fuel-based power sources (Dai et al., 2020). SSE is a “land-to-ship electricity connection that replaces the AEs to supply power to the ship when at berth” (Yu et al., 2019, p.202). The EU has been increasingly proactive in promoting the use of SSE, with its first important directive being in 2005, which mandates ships berthing in EU ports for more than 2 hours to use fuel oils with a sulphur content of less than 0.1% (e.g., Marine Gasoline Oil (MGO)), unless they are able to switch to SSE (Castells Sanabra et al., 2014; Zis, 2019). It took one step further in 2014 when it approved the directive 2014/94/EU stating that “Member States shall ensure that the need for shore-side electricity supply for inland waterway vessels and sea-going ships in maritime and inland ports is assessed in their national policy frameworks, where, such shore-side electricity supply shall be installed as a priority in ports of the TEN-T Core Network, and in other ports, by December 31, 2025, unless there is no demand and the costs are disproportionate to the benefits, including environmental benefits” (Innes and Monios, 2018, p.300). Here, the costs mainly refer to the installation of SSE port-side infrastructure and the supplied electricity from the grid (Zis, 2019), with the environmental benefits being the reduced socio-environmental external costs associated with the use of SSE against MGO (Spengler and Tovar, 2021). External costs are the economic consequences of ship exhaust emissions on the local population and environment (Nunes et al., 2019). Along with ports, there are also shipowner costs in the form of ship-side modifications and the payment for supplied power (Winkel et al., 2016), although in return the majority of the fuel costs are avoided. Hence, the choice of deploying SSE requires the comparison of the associated costs and benefits, where the costs are split into “port-side” and “ship-side”,

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[*] Corresponding author.
E-mail address: KETAN.GORE.2019@MUMAIL.IE (K. Gore).

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with the incurred benefits being the reduced external costs and the saved fuel costs when ships switch to SSE instead of using MGO at berth. Also, when conducting SSE cost-benefit analysis, it is important to consider the energy mix of the supplied electricity, as it will drastically impact the associated socio-environmental benefits (Spengler and Tovar, 2021).

Investigating SSE-related costs and benefits is a key feature of extant literature. Tzannatos (2010) reported total external costs of €10.8 million and €1.4 million for the use of MGO and SSE by cruise ships berthing in the Piraeus port, respectively, with the total “ship-side” private costs being €5.2 million and €10.4 million, respectively. Ballini and Bozzo (2015) reported total private costs of €37 million for “port-side” SSE installation in the Copenhagen cruise port and external costs savings of €2.8 million annually, for SSE usage by 60% of berthing cruise ships, resulting in a payback period of 12–13 years. Tseng and Pilcher (2015) estimated total external costs savings of $2.8 million (only NO_x and CO_2) for 60 container ships berthing in the Kaohsiung port using SSE, alongside an increase in private costs per ship of $6920. Innes and Monios (2018) estimated total private “port-side” costs of €7.4 million for SSE installation in a medium-sized port (Aberdeen), and assessed that total external costs savings could be up to €1.4 million annually, resulting in Net Present Values (NPVs) of €1.2 million (10 year period) and €8.7 million (25 year period). Dai et al. (2019) reported negative NPVs in range of −1.3 billion to −2.9 billion Chinese Yuan (CNY) for SSE usage by containerships in Shanghai port, for three adoption rates, incorporating CO_2 emission trading only. Yu et al. (2019) estimated an average payback period of less than 4 years for the use of SSE by containerships visiting Dalian port, with the total external cost savings being $128 million annually. Winkel et al. (2016) estimated the total external cost savings with the prospective use of SSE across several European (including Irish) ports to be €2.94 billion, while for a similar scenario, Stolz et al. (2021) indicated significant achievable reductions in shipping emissions (3 million tons CO_2, 86,431 tons NO_x, 4130 tons SO_x and 1596 tons $PM_{2.5}$).

Despite the extant literature on costs and benefits of using SSE, gaps still remain to be addressed. Firstly, except for Innes and Monios (2018), studies have not analysed the impact of the future energy mix for grid supply, an important aspect when assessing the profitability of long term investments such as SSE. Within the EU, significant changes are expected in the future energy mix, with an estimated increase in the uptake of renewable energy sources from 34% (year 2019) to 65% (year 2030), as a part of newly proposed European green deal (European Commission, 2020, European Environment Agency, 2022). Although Innes and Monios (2018) outlined the socio-environmental benefits arising from the considered baseline (year 2015) and future (year 2020) Scottish energy mix, there was no discussion on the subsequent changes in the supplied electricity price, as this will also impact the overall cost-effectiveness of using SSE. Secondly, it was observed that researchers have rarely examined the costs and benefits of SSE based on the variance in its levels of adoption. While it has been suggested in the past that switching high visiting frequency ships to SSE could be advantageous (Innes and Monios, 2018), it is important to provide a detailed cost-benefit analysis under a range of different scenarios to assist with the identification of most profitable pathway for implementing SSE. Thirdly, previous studies have rarely assimilated both the port-side and the ship-side installation costs with that of achieved socio-environmental benefits through reduced external costs alongside the economic benefits from saved fuel costs while conducting SSE feasibility studies. Fourthly, it was seen that despite having one of the highest death rates in the world due to shipping emissions (Rutherford and Miller, 2019), Ireland was never subject to a SSE cost-benefit case study. To address these gaps, this research conducts a cost-benefit analysis of SSE investment at six different levels of its implementation, considering the current (year 2019) and future (year 2030) Irish energy mix, using the NPV approach, assimilating the port-side and ship-side installation costs and the incurred benefits through reduced external costs and saved fuel costs.

Based on Spengler and Tovar (2021), enabling all the national ports and visiting ships to use SSE will be practically impossible due to high capital costs, and hence, the initial focus should be on the ports situated in highly populated cities, and for those ships which present the highest energy demand at berth and often visit same port multiple times (Zis, 2019). For these reasons, this case study will focus on Dublin and Belfast, the two most populated cities in Ireland (Northern Ireland Statistics and Research Agency, 2019; Central Statistics Office, 2022a), and on passenger (i.e. Roll/on-Roll/off (Ro-Ro) ferries and cruise) ships, which are known to make frequent port calls and have, globally, displayed higher energy demand at berth when compared to that of cargo ships (Winkel et al., 2016; Spengler and Tovar, 2021).

2. Materials and methods

2.1. Geographical scope

Being an island nation, maritime transportation is the backbone of the Irish economy, with its ports acting as the important gateways for trade and tourism. Irish merchandise export volume in 2019 stood at 18.5 million tonnes, with 90% of the exported tonnage being moved through Irish ports (Irish Maritime Development Office [IMDO], 2020). Ireland is separated into two jurisdictions, the Republic of Ireland and Northern Ireland. Dublin, the capital of the Republic of Ireland and the most populated city in the nation (Central Statistics Office, 2022a), accounts for almost 50% of the national maritime trade (IMDO, 2021). Belfast, the capital of Northern Ireland handles 70% of the Northern Irish seaborne trade and hosts the majority of the Northern Irish population (Northern Ireland Statistics and Research Agency, 2019; McDonnell, 2020). Within Europe, the share of Ro-Ro ferries in the total seaborne freight was the highest for Ireland (31.6%) (Eurostat, 2021), indicating the significance of this ship type in the Irish maritime economy. Several popular ferry companies such as Stena Line, P&O ferries, Seatruck ferries and Irish ferries offer connectivity to British and mainland European ports. More than 4.5 million ferry passengers transited through Irish ports in 2019, with Dublin and Belfast ports combined representing 75% of the total volume (IMDO, 2020). Along with ferries, cruise ships have also played a significant role in boosting Ireland’s tourism economy. More than 700,000 passengers arrived in Ireland in 2019 through cruise ships, with Dublin and Belfast remaining the most dominant cruise ports, accounting for 70% of the total passengers (IMDO, 2020).

2.2. Estimation of ship emissions

2.2.1. Onboard operation

For all passenger ships which berthed in Dublin and Belfast ports during 2019, the total AE emissions from the onboard use of MGO were determined by Eq. (1), as derived from Tzannatos (2010):

$$E_{MGO} = \sum_{i} \left(T_B \times \left[P_{AE} \times LF_{AE} \times EF^{i}_{AE} \right] \times 10^{-6} \right) \tag{1}$$

Where E_{MGO} is the total emissions from MGO usage (tons), i refers to the pollutants: SO_2, NO_x, $PM_{2.5}$ and CO_2, T_B is the time spent at berth (hours), P_{AE} is AE power (kW), LF_{AE} is the load factor of the AE at berth (in %) and EF^{i}_{AE} is the emission factor of the AE for each emitted pollutant (g/kWh).

For this study, our dataset was built from statistics on ship movements and specifications obtained from the Refinitiv Refinitiv Eikon, 2022 AIS database. From the AIS dataset, it was observed that 34 and 59 passenger ships berthed in Dublin and Belfast during 2019 registering 3618 and 1046 port calls, respectively. As the 2005/33/EU directive does not apply to calls at berth made for less than 2 h, such movements were excluded from the study, representing only 21 of the total 4664 port calls being made across Dublin and Belfast ports. Information on

P_{AE} and T_B for the ships under investigation was retrieved from the AIS dataset. LF_{AE} for each ship was assigned based on the study of De Meyer et al. (2008). The allocation of EF^i_{AE} depends upon the considered fuel type (in this instance, MGO) and on the ship engine type (Tzannatos, 2010). Based on the study of Spengler and Tovar (2021), we assumed that auxiliary engines are of the "medium speed diesel" type for the selected ships. EF^i_{AE} was assumed as 0.42 g/kWh for SO_2, 13.9 g/kWh for NO_x, 0.17 g/kWh for $PM_{2.5}$ and 690.71 g/kWh for CO_2 (Inner City Fund, 2009).

2.2.2. SSE operation

The use of SSE by ships at berth will generate additional electricity requirements from the local power grid (Tzannatos, 2010). Within the SSE operation, ships while at berth will be required to use their AEs for 1 h to connect and disconnect from the external power supply in port (Zis, 2019). Associated emissions from the SSE operation can be calculated by Eq. (2):

$$E_{SSE} = \sum_i \left(\left(T_B - T_{CHANGEOVER} \right) \times \left[P_{AE} \times LF_{AE} \times EF^i_{SSE} \right] \times 10^{-6} \right) + \left(T_{CHANGEOVER} \times \left[P_{AE} \times LF_{AE} \times EF^i_{AE} \right] \times 10^{-6} \right) \quad (2)$$

Where E_{SSE} is the total emissions from the SSE operation (tons), i refers to the pollutants: SO_2, NO_x, $PM_{2.5}$ and CO_2, T_B is the time spent at berth (hours), $T_{CHANGEOVER}$ is the total changeover time for shore-side power connecting and disconnecting (estimated at 1 h), P_{AE} is AE power (kW), LF_{AE} is the load factor of the AE at berth (in %), EF^i_{SSE} is the grid emission factor for each emitted pollutant (g/kWh) and EF^i_{AE} is the emission factor of AE for each emitted pollutant (g/kWh).

In 2019, a total of 31.3 TW h of electricity was produced in Ireland, with the share of renewable energy sources being 37.57% (Sustainable Energy Authority of Ireland [SEAI], 2020). Recently, Ireland has committed to reduce its dependence on non-renewable sources in electricity production, by increasing the uptake of renewable energy sources to 80% by 2030, 15% higher than the EU target (European Commission, 2020, Grid Beyond, 2021). Within the renewables sector, wind and solar energy have been receiving the topmost priority from the Irish government to meet the set 2030 targets (Department of Environment, Climate and Communications, 2022). Based on the projected capacity of renewable energy production in 2030, it is estimated that wind will fulfil 61% of the total Irish energy demand, with solar fulfilling 19% (Turner and Zhang, 2018). While for the non-renewable sector, the use of coal, peat and oil is expected to be phased out before the end of 2030 (Environmental Protection Agency, 2020), with gas remaining the only major contributor (Grid Beyond, 2021), to meet the remaining 20% of the Irish energy demand. Fig. 1 indicates the structure of the Irish energy mix in present year 2019 and the prospective mix in year 2030.

Such changes in the overall structure of the energy mix are also expected to impact the cost-effectiveness of using SSE against MGO as the grid emission factors will be changing accordingly, affecting the derived socio-environmental benefits. Table 1 provides the grid emission factors for year 2019 and 2030 energy mix, which were simulated based on the information in SEAI (2020), Environmental Protection Agency (2021) and SEAI (2021).

2.3. External cost estimation

Following established research on external cost assessment using the top-down approach (Tichavska and Tovar, 2015; Nunes et al., 2019; Spengler and Tovar, 2021), a similar methodology was also adopted in this research. The top-down approach involves the estimation of external costs using cost factors from reference bottom-up studies (e.g., Benefits Table database (BeTa) and Clean Air For Europe (CAFE) and New Energy Externalities Development for Sustainability (NEEDS)) (Nunes et al., 2019).

BeTa provides external cost factors for NO_x, SO_2 and $PM_{2.5}$ depending on the zone (urban (short-range externality) or rural (long-range externality)) and population density for 14 EU member states (including Ireland) (Holland and Watkiss, 2002). In 2005, the external cost factors (rural) for BeTa were updated by the CAFE project, covering

Table 1
Grid emission factor for year 2019 and year 2030 energy mix.

Energy mix	Grid Emission factor (g/kWh)			
	SO_2	NO_x	CO_2	$PM_{2.5}$
Year 2019	0.071	0.191	324.5	0.008
Year 2030	0.041	0.110	186.91	0.004

Source: Data based on SEAI (2020), Environmental Protection Agency (2021), SEAI (2021).

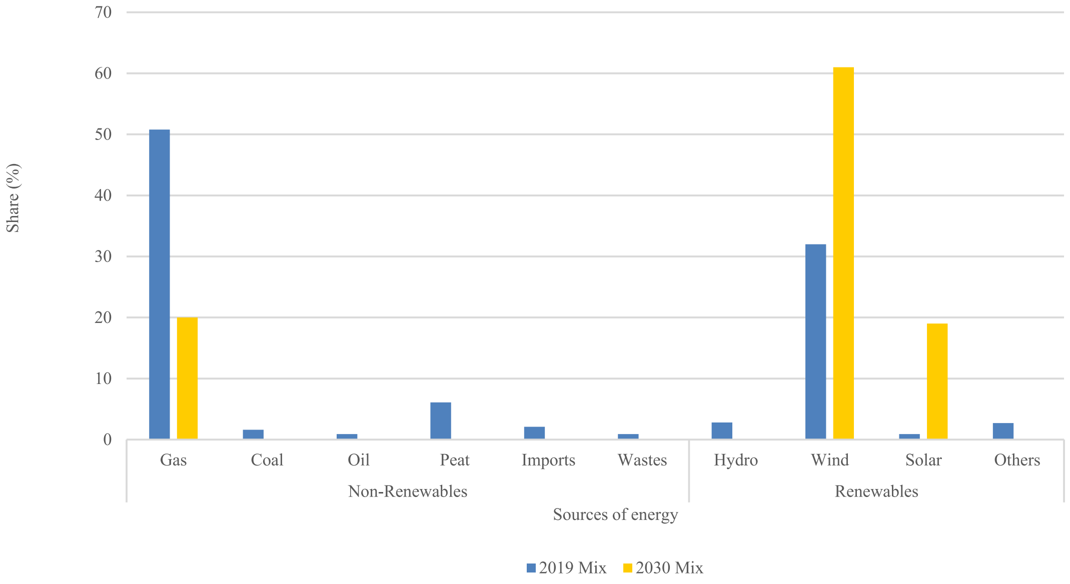


Fig. 1. Irish energy mix in 2019 and prospective 2030 mix.
Source: Turner and Zhang (2018), SEAI (2020), Grid Grid Beyond, 2021.

25 EU member states and forecasted for a 2010 baseline scenario (Holland et al., 2005; Nunes et al., 2019). The size of the port city is used as a guide to calculate the external costs of emitted pollutants, with an additional rural externality for the country the port is situated within (Holland and Watkiss, 2002). Studies have frequently used the combination of BeTa (urban) and CAFE (rural) cost factors to enhance the estimation of external costs (Castells Sanabra et al., 2014; Tichavska and Tovar, 2015; Nunes et al., 2019) and therefore a similar approach was adopted in this study. For urban cost estimation, external cost factors for SO_2 and $PM_{2.5}$ suggested in BeTa for a city of 100,000 people must be multiplied by a scale factor, which is linear up to 500,000 inhabitants, to adjust the provided cost factors in line with the respective population of Dublin and Belfast. In this study, linearity of the scale was assumed. Data on the population of Dublin (554,600 in 2016) and Belfast (333,871 in 2011) was obtained from Northern Ireland Statistics and Research Agency (2019) and Central Statistics Office (2022a), and adjusted by 4% and 7%, respectively, based on the increase in the total Irish population from the two reference years until 2019 (Eurostat, 2022a). The derived year 2019 numbers were further incremented by 7.4% (for Dublin) and 2% (for Belfast) to adjust as per the projected increase in 2030 population figures (Central Statistics Office, 2022b, Office for National Statistics, 2022). CAFE provides rural cost factors for four different settings which vary due to ways to value mortality rates, the size of the effects on health and the differential impact of cut-off points for ozone impact (Nunes et al., 2019). To homogenise all these scenarios, average results for the four sensitivity scenarios were considered when allocating the rural cost factors.

Along with BeTa and CAFE, the NEEDS project has been used as an apposite methodology for assessing the external costs of maritime transport (within sea regions) (Maragkogianni and Papaefthimiou, 2015; Tichavska and Tovar, 2015; Nunes et al., 2019). However, it should be noted that the NEEDS approach does not include both urban and rural cost factors, which would underestimate the total external costs from shipping emissions (Nunes et al., 2019). Also, BeTa makes explicit mention of air pollution damage in port areas caused by shipping, which is not the case in NEEDS (Nunes et al., 2019). Given the importance of this specific damage, it can be said that using a combination of BeTa and CAFE cost factors seems to be a more reliable approach to estimating external costs when investigating the achieved socio-environmental benefits of a port-based emission reduction technology like SSE. For CO_2, the external cost factor was derived from the CE Delft report, where the “average” cost factor of €86/ton was assumed (Van Essen et al., 2011).

Cost factors provided in the BeTa and CE Delft report refer to the year 2000 and 2008 prices, respectively, while CAFE reflects the year 2010 prices. The Consumer Price Index (CPI) for Ireland as available in the Organisation of Economic Co-operation and Development (OECD) statistical profiles was used to update these prices to 2019 levels (OECD, 2022). According to OECD (2022), the Irish CPI in 2019 was 101.8, while the CPI was 74.8, 100.9 and 95.3 in the year 2000, 2008 and 2010, respectively. To adjust for the year 2030 prices, Irish CPI projections as in PwC (2022) were utilised. The long term CPI rate (to end of the 2020s) is forecasted to be 2% (PwC, 2022), hence, there will be an increment of 22% in the considered year 2019 prices to reflect the prospective year 2030 prices. Table 2 presents calculated external cost factors for NO_x, SO_2, $PM_{2.5}$ and CO_2, considering the port cities of Dublin and Belfast.

Table 2

Updated Dublin and Belfast external cost factors for NO_x, SO_2, $PM_{2.5}$ and CO_2.

Ports	Dublin			Belfast		
Pollutant	BeTa Urban	CAFE Rural	Total	BeTa Urban	CAFE Rural	Total
	Year 2019 (€/ton)					
NO_x	3556	7414	10,970	3556	7414	10,970
SO_2	43,951	9514	53,465	27,222	9514	36,736
$PM_{2.5}$	241,730	28,701	270,431	149,720	28,701	178,421
CO_2	–	–	86	–	–	86
	Year 2030 (€/ton)					
NO_x	4338	9045	13,383	4338	9045	13,383
SO_2	57,588	11,607	69,195	33,875	11,607	45,482
$PM_{2.5}$	316,734	35,015	351,749	186,312	35,015	221,327
CO_2	–	–	105	–	–	105

Source: Based on Holland and Watkiss (2002), Holland et al. (2005), Van Essen et al. (2011).

2.4. Private cost valuation

2.4.1. Onboard operation

Following Tzannatos (2010), no extra costs are required for installation of AEs as they will be available onboard the ships no matter the level of SSE adoption. Ship-side private costs for onboard operation are the fuel and maintenance costs of using AEs at berth (Tzannatos, 2010). The total fuel costs incurred can be estimated as a function of total fuel consumed by AEs while at berth, which can be calculated using the following Eq. (3):

$$FC_{MGO} = T_B \times [P_{AE} \times LF_{AE} \times SFC] \times 10^{-6} \quad (3)$$

Where FC_{MGO} is the total fuel (MGO) consumed (tons), T_B is the time spent at berth (hours), P_{AE} is AE power (kW), LF_{AE} is the load factor of the AE at berth (in %) and SFC is specific fuel consumption (g/kWh). For medium speed engines and the onboard use of MGO, SFC was assumed to be 217 g/kWh (Inner City Fund, 2009). Further, total fuel costs depend upon fuel prices (Tzannatos, 2010). The “Rotterdam” bunker fuel price (on December 31, 2019) of €536.8/ton was assumed for MGO (Shipandbunker, 2022). The price listed in \$/ton was converted to €/ton using conversion rates as of “December 31, 2019” from European Central Bank (2022). The maintenance cost for the operation of AEs was taken at €0.014/kWh (Perčić et al., 2020). As the average brent crude price in 2030 is expected to be at \$73/barrel, around 12.33% higher than the average brent crude price in 2019 (\$64/barrel) (United States Energy Information Administration, 2020; Wong, 2022a), hence, the MGO price estimate for the year 2030 was considered to be €603/ton. Further, the AE maintenance costs were incremented by 22%, based on the projected Irish CPI rate.

2.4.2. SSE operation

2.4.2.1. *Ship-side SSE costs.* The ship-side private costs of SSE will include the fuel costs for running the AE for 1 h (changeover time) which are estimated as a function of fuel consumed during the required process, as noted in Eq. (4):

$$FC_{CHANGEOVER} = T_{CHANGEOVER} \times [P_{AE} \times LF_{AE} \times SFC] \times 10^{-6} \quad (4)$$

Where $FC_{CHANGEOVER}$ is the total fuel consumed during the changeover process (tons), $T_{CHANGEOVER}$ is the time for power connecting and disconnecting (1 h), P_{AE} is AE power (kW), LF_{AE} is the load factor of the AE at berth (in %) and SFC is specific fuel consumption (g/kWh). We have assumed, as per Whall et al. (2010) that passenger ships used either Marine Distillate Oil (MDO) (1.5% sulphur) or MGO, during changeover time. For ships using MDO, SFC was assumed 217 g/kWh (Whall et al., 2010), with the “Rotterdam” bunker fuel price (on December 31, 2019) being €539.9/ton (Shipandbunker, 2022), where, the price in \$/ton was converted to €/ton based on currency conversion rates (European Central Bank, 2022). Further, the considered MDO price was incremented by 12.33%, to adjust for the year 2030 estimate. While for ships using MGO, SFC and fuel prices (year 2019 and 2030) as assumed in section 2.4.1 were considered, along with the maintenance cost of AEs.

To allow for SSE operation, it was assumed that any required installation must be retrofitted on the considered passenger ship, the data for which was obtained from an EU-based study by De Jonge et al. (2005). As the baseline year for this study was 2005, the given prices were updated to the 2019 levels based on the changes in EU-27 and Irish CPI (OECD, 2022). The year 2019 retrofit costs were incremented by 22% to obtain an estimate of the year 2030 costs. Table 3 shows the updated retrofit costs and lifespan of the ship-based SSE equipment's.

The final costs for SSE utilisation will also include electricity as well as system maintenance costs. In this study, we have assumed the perspective of port authority towards the use of SSE to be "neutral", where, the port sells the power to the ships at exactly the cost of purchasing it from the power station (Zis, 2019). In such an instance, all the electricity costs will be passed on to the shipowners. In 2019, the cost of electricity in Ireland for non-household consumers was €0.1294/kWh (Eurostat, 2022b). To obtain an estimate of the "year 2030 electricity price", an assumption would have to be made based on the prospective energy mix. By compiling the average "year 2030" Irish wind (onshore and offshore) and solar electricity costs (Turner and Zhang, 2018), and the projected gas prices in 2030 (Wong, 2022b), based on their share in the total energy mix, the final electricity price in 2030 was estimated to be €0.0848/kWh. Along with electricity, the maintenance cost of using SSE was also assumed to be passed onto the ships (De Jonge et al., 2005). For the years 2019 and 2030, a SSE maintenance cost of €0.00754/kWh and €0.0092/kWh was assumed, respectively, based on the update of prices in De Jonge et al. (2005) to 2019 and 2030 levels.

2.4.2.2. Port-side SSE costs. The port-side private costs will primarily be the retrofit costs of the required SSE-related equipment for the existing berths in Dublin and Belfast ports. The costs for retrofitting berths with SSE technology were obtained from an EU-based study by De Jonge et al. (2005), where the given costs were updated to 2019 levels based on the changes in EU-27 and Irish CPI (OECD, 2022). Due to the considerably longer lifespan of SSE port-side equipment, there will be no re-installation costs over the period under investigation in this study. Table 4 shows the updated retrofit costs and lifespan of the port-based SSE equipment's.

Currently, there are 11 passenger berths in Dublin port, while in Belfast, there are 9 passenger berths (4AllPorts, 2015, Dublin Port, 2019; Dublin Port, 2022). Fig. S.1 and Fig. S.2 in the supplementary material highlights the location of these passenger berths within Dublin and Belfast ports, respectively.

2.5. *Scenario development: berth allocation*

To make a comparison between the existing system of using MGO and the possible use of SSE as its replacement, we developed six scenarios representing different levels of implementation, separately for passenger ships calling in Dublin and Belfast ports, identified as follows:

(A) Top 5 frequent ship callers switch from MGO to SSE
(B) Top 10 frequent ship callers switch from MGO to SSE
(C) Top 15 frequent ship callers switch from MGO to SSE
(D) Top 20 frequent ship callers switch from MGO to SSE
(E) Top 25 frequent ship callers switch from MGO to SSE
(F) All ship callers switch from MGO to SSE

To estimate the number of berths to be retrofitted under each scenario, assumptions have to be made. From Table 5, the combined "average berthing time" for top 5 callers in Dublin was 24.21 h, i.e., on average each ship spent 4.84 h at berth in a single day. Since it will not be feasible to accommodate all these ships on a single SSE-retrofitted berth in one day, hence, we assumed that 3 berths will be allocated to allow for smoother operation. Similar assumptions were also made for other scenarios.

Table 3
Updated retrofit costs and lifespan of ship-based SSE equipment's (per ship).

Equipment	Year 2019		Year 2030	
	Cost (€)	Lifespan (years)	Cost (€)	Lifespan (years)
Ship transformer cost	337,873	10	412,205	10
Cable cost	4524	12.5	5519	12.5

Source: Calculated based on De Jonge et al. (2005).

Table 4
Updated (2019) retrofit costs and lifespan of port-based SSE equipment's (per berth).

Equipment	Cost (€)	Lifespan (years)
High Voltage Electricity Connection	617,120	30
High Voltage Cable Installation	211,120	40
Fixed Cable Reel System	176,320	30
Electricity Converter	507,500	20

Source: Calculation based on De Jonge et al. (2005).

Table 5
Combined "average berthing time" and estimated number of passenger berths retrofitted in Dublin and Belfast, for six SSE scenarios.

Scenario	Dublin		Belfast	
	Berthing time (hours/day)	SSE berths	Berthing time (hours/day)	SSE berths
Top 5 Callers	24.21	3	13.93	2
Top 10 Callers	41.04	6	14.95	3
Top 15 Callers	41.59	7	15.64	4
Top 20 Callers	41.86	8	16.17	5
Top 25 Callers	42.09	9	16.45	6
All Callers	42.72	11	18.46	9

Source: Own elaboration based on AIS data

2.6. *Cost-benefit assessment for implementing SSE*

To evaluate the financial and socio-environmental attractiveness of implementing SSE, we calculated the NPV for the investment, using Eq. (5):

$$NPV = -CAPEX_{SSE} + \sum_{t=1}^{n} \left(\left(B^{EC} + B^{Fuel} \right) - OPEX_{SSE} \right) \Big/ (1+r)^{t} \tag{5}$$

Where NPV is the net present value (€), $CAPEX_{SSE}$ is the capital (investment) costs of SSE port and ship retrofit (€), n is the duration of the installation (years), B^{EC} is the total socio-environmental benefits achieved (i.e. saved external costs) with the use of SSE against MGO (€), B^{Fuel} is the total benefits achieved from the avoided MGO fuel and AE maintenance costs while using SSE (€), $OPEX_{SSE}$ is the annual operation and maintenance costs (fuel and AE maintenance costs during change-over process, as well as electricity and maintenance of installed SSE technology) (€), r is the discount rate and t represents time periods. Because ships will be required to replace their onboard transformer after every 10 years to be able to use SSE, we assumed the maximum duration of this installation as 10 years. We took the Irish social discount rate of 4% (Department of Public Expenditure and Reform, 2019).

3. Results and discussion

3.1. *Results*

In the present scenario of consuming MGO for onboard AE operation, the total emissions during 2019 for all passenger ships berthing in Dublin and Belfast ports stood at 35,005 tons and 16,247 tons, respectively. From the compiled ship emissions in Dublin and Belfast, CO_2 was found to be the most dominant pollutant in both cases (97.95%), followed by NO_x (1.97%), SO_2 (0.06%) and $PM_{2.5}$ (0.02%). Fig. 2 shows the total emissions from the use of MGO for the six scenarios developed based on the frequency of ship callers in Dublin and Belfast. Overall, it was observed that ships with the most frequent calls in the respective ports also contributed the most to the total emission levels.

The outcomes of a comparison of MGO versus SSE emissions across the six scenarios in Dublin and Belfast ports is shown in Fig. 3. In all scenarios, emission levels improved significantly in comparison to the current option of MGO. The reductions in overall emissions were higher when supplying ships with SSE from a comparatively "cleaner" year 2030 grid than the one being used in 2019, due to higher projected uptake of renewable energy sources in the former.

For the exclusive use of SSE (year 2019 grid) by all the ships in Dublin and Belfast ports, a reduction of 41.5% and 46.5% in the overall emissions from the use of MGO was observed, respectively, with similar reductions (in %) visible for other scenarios as well. When using SSE from the prospective year 2030 grid, the reductions from the use of MGO in Dublin and Belfast ports were nearly twofold. While implementing SSE certainly enables a significant reduction in emissions, however, it leads to a substantial increase in private costs. The increase in private costs can be attributed to capital costs arising from ship-side and port-side retrofits of SSE-related equipment, hourly usage of fuel during the changeover period and most importantly, the electricity costs. Based on the allocated berths, port-side installation costs were calculated alongside the respective ship-side costs for each of the considered scenarios. The derived private costs for SSE usage were later summed up with the respective external costs generated under each scenario, and compared against the costs of using MGO under similar scenarios. Fig. 4 shows the annualised private and external "year 2019" and "year 2030" costs from the usage of MGO and SSE for six scenarios, in Dublin and Belfast ports.

From Fig. 4, it was observed that in each of the considered scenarios, under current (2019) and future (2030) grid supply, the total annualised costs of using SSE were lower than that of MGO, mainly due to lesser external costs being generated through the use of SSE technology. The total external costs from the exclusive use of SSE (year 2019 grid) by all ships berthed in Dublin and Belfast stood at €7.70 million and €2.07 million, respectively. These figures were lower by 44.6% (for Dublin) and 65.1% (for Belfast) than that from MGO (year 2019) external costs, with similar reductions (in %) visible for other scenarios as well. The total external costs of €8.85 million and €2.15 million were generated for the use of SSE (year 2030 grid) by all ships in Dublin and Belfast, respectively. This indicates a reduction of 47.93% (for Dublin) and 69.91% (for Belfast) than that from MGO (year 2030) external costs.

To determine the overall feasibility of using SSE i.e., if the total benefits achieved in the form of saved external and fuel costs outweigh the total private costs over the considered time period, NPV analysis was conducted for different scenarios of SSE implementation. In general, a positive NPV will indicate that the use of SSE over MGO is profitable, with the scenarios reflecting higher positive NPVs being deemed more attractive to implement. Fig. 5 indicates the estimated NPVs using a 10-year time horizon for six scenarios of SSE implementation in Dublin and Belfast ports, considering an estimate of "year 2019" and "year 2030" costs.

Findings from Fig. 5 reveal that owing to positive NPVs, introducing SSE seems feasible for all scenarios in Dublin port. Due to a negative NPV of −€3.50 million, switching all passenger ships to SSE in Belfast will remain inviable as per year 2019 costs. A significant boost in NPVs (by 50%) for all scenarios is expected when considering the year 2030 costs, which is mainly due to higher benefits incurred in the form of saved external costs alongside the lower electricity costs, resulting from increased use of renewable energy sources in year 2030 grid. For the most viable scenario (by NPV) observed in Fig. 5 (SSE for top 10 callers), we conducted a sensitivity analysis to investigate the subsequent changes in year 2019 and year 2030 NPVs, with changes in electricity and fuel price in either direction, as shown in Fig. 6.

From Fig. 6, it is observed that an increment in the year 2019 electricity price by 90% and 100% will result in negative NPV for SSE utilisation by top 10 callers in Dublin and Belfast, respectively. Furthermore, in spite of a detrimental increase of 150% in the projected year 2030 electricity price, both the NPVs remained positive. Also, even a drop of 95% in the considered year 2019 and year 2030 fuel price will not generate negative NPV.

3.2. Discussion

From section 3.1, it was observed that switching all passenger ships to SSE in Dublin with 2019 energy mix will reflect a positive NPV, although the same could not be said for Belfast. This result was due to higher applied private costs in Belfast, primarily from ship-side retrofits, as around 59 passenger ships visited Belfast, compared to 34 in Dublin. Overall, the adoption of SSE for the top 10 frequent passenger callers seems the most attractive option, as it presented the highest positive NPV amongst the studied scenarios. When comparing with previous studies, the estimated NPVs in Dai et al. (2019) were found to be effectively negative, probably due to the exclusion of external cost savings from the analysis, with more ships being considered for retrofit (12,000). Innes and Monios (2018) considered external costs savings, and their estimated NPV for Aberdeen was comparatively lower than that for Dublin, as shown in this study, possibly due to higher population level of Dublin, which garnered significant external cost savings. For studies such as Ballini and Bozzo (2015) and Yu et al. (2019), the use of SSE also seemed viable with lower payback periods, albeit only at

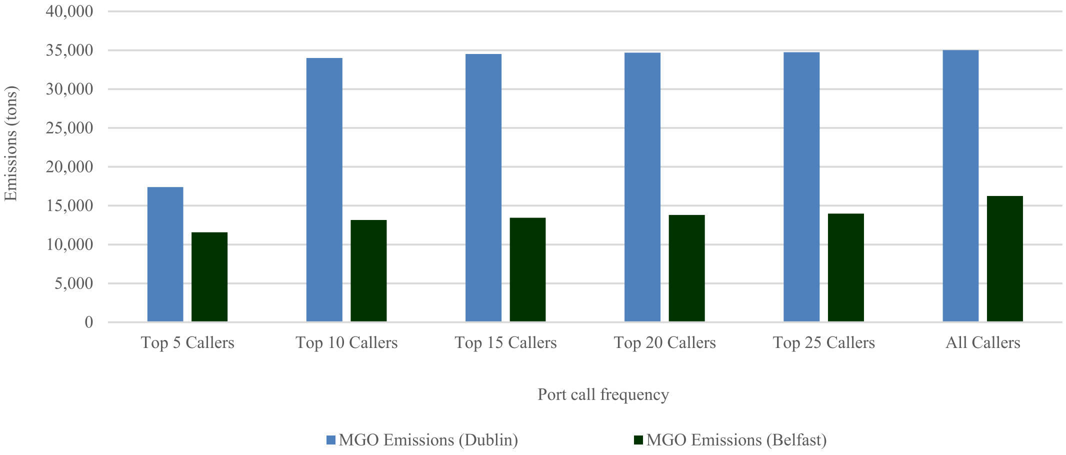
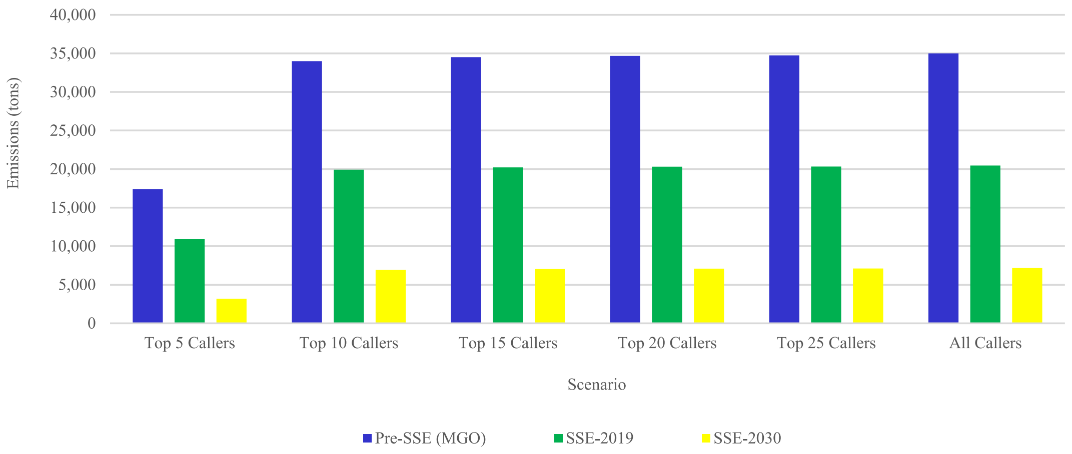
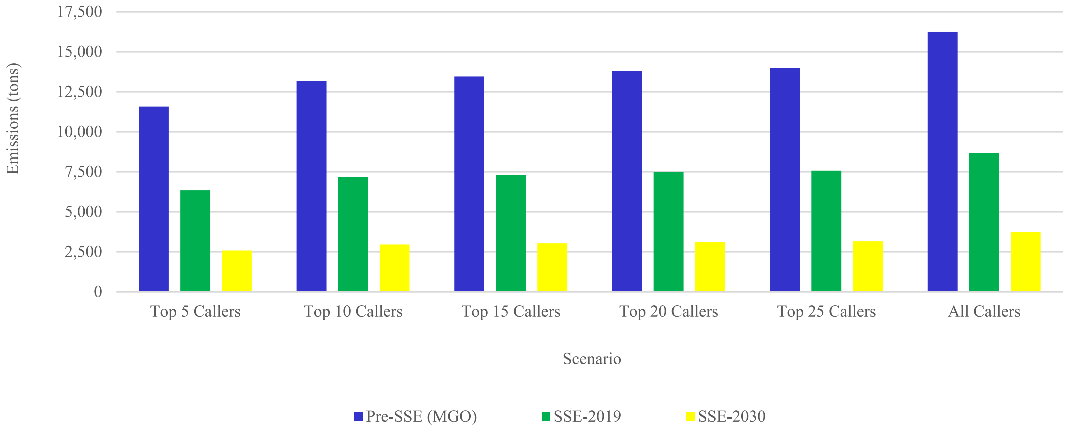


Fig. 2. Contribution of frequent ship callers to the total MGO emissions in Dublin and Belfast.



(a) Emissions in Dublin



(b) Emissions in Belfast

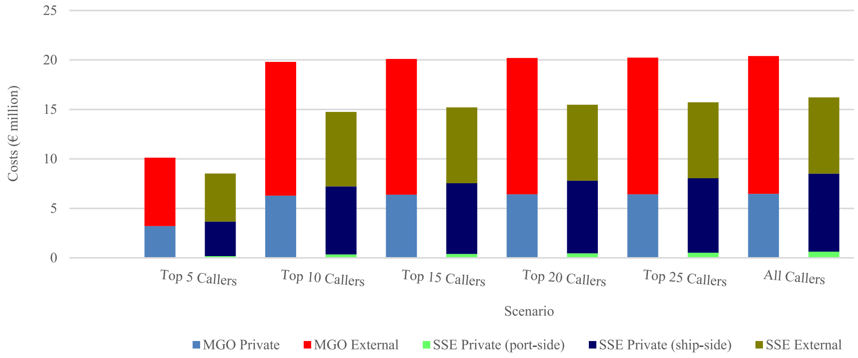
Fig. 3. Emission levels for MGO and SSE in six scenarios, for Dublin and Belfast.

port-side and ship-side levels, respectively. Also, similarly to this study, Tzannatos (2010) showed lower total (private + external) annualised costs for SSE against MGO. Overall, the studies which considered external cost savings showed either lower payback periods (or costs) or positive NPVs, reflecting its significance while evaluating the cost-effectiveness of SSE.

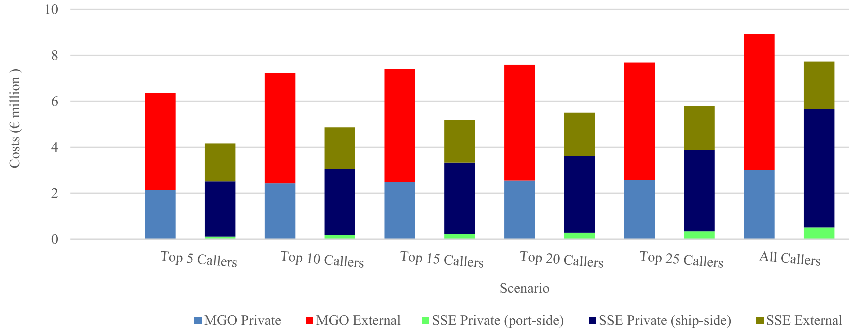
The main challenge with SSE deployment is that the ports and shipowners that will have to invest in the necessary infrastructure are not the ones who benefit from the reduced emission levels (Winkel et al., 2016). To help ports recover the invested retrofit costs, subsidies would be required. According to the European Sea Ports Organisation (2021), so far, every SSE facility established in European ports has been supported by up to 50% of public financing. The total port-side retrofit costs in Dublin and Belfast stood at €9.07 million and €4.54 million, respectively, for the optimal scenario (SSE for top 10 frequent callers). In the best possible case, it is expected that public financing will cover at least €4.54 million and €2.27 million of invested costs, respectively. Further, Dublin and Belfast ports may decide to put a markup of €0.0122/kWh (i.e., increment electricity price by 8.62%) and €0.0144/kWh (i.e., increment electricity price by 10.01%), respectively, as this will help recover the remaining 50% of retrofit costs in 10 years. For shipowners, the tactics could be to increase the passenger ticket price to recover the paid costs. For example, from the AIS dataset, the top 10 frequently calling ships in Dublin and Belfast have a combined passenger capacity of 10,292 and 15,234, respectively. By compiling this information with the number of annual calls being made alongside the total ship-side costs, we observed that the top 10 callers to Dublin and Belfast can increment their ticket prices by €0.03 and €0.04 (per passenger seat) every year, respectively, to recover the total costs over the course of the next 10 years.

4. Uncertainties and limitations

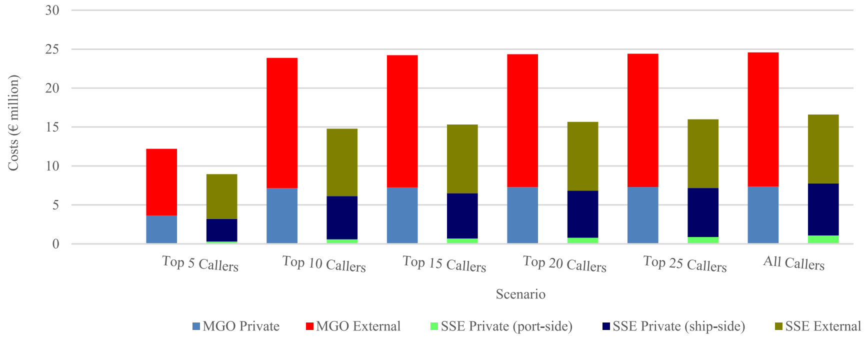
Despite the methodological contributions of this study, there remains some uncertainties and limitations. It should be noted that the supplied electricity and fuel prices tend to fluctuate quite frequently, which will affect the overall costs and benefits of SSE implementation. With the ever-changing global geo-political situation, these conditions have now become even more relevant, since it was observed that the electricity and fuel prices (as of early 2022) have reached an all time high, especially within the EU (Batlle et al., 2022; Shipandbunker, 2022). Currently, the major source of electricity production within Ireland and the EU is imported natural gas, which has shown a high volatility in terms of available spot price and subsequently, has been the main driver behind high electricity prices (Batlle et al., 2022). To reduce their dependence on such highly priced, volatile, and non-renewable commodity, Ireland and the EU have prioritised the use of wind and solar energy sources for the majority of their electricity production by 2030, thus improving their energy sovereignty (European Commission, 2020, Grid Beyond, 2021). Although electricity production costs from



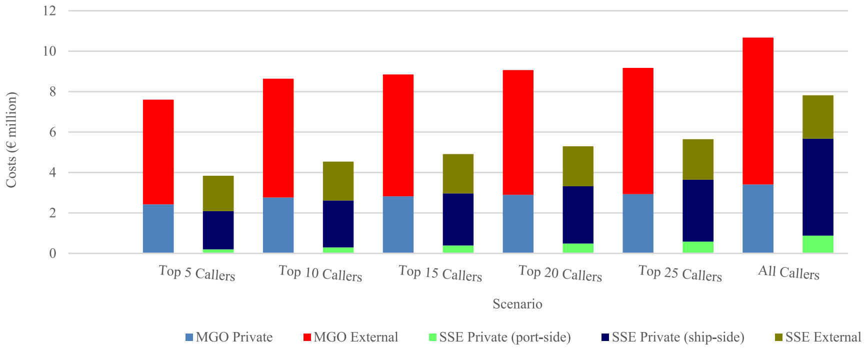
(a) Annualised (Year 2019) costs in Dublin



(b) Annualised (year 2019) costs in Belfast



(c) Annualised (year 2030) costs in Dublin



(d) Annualised (year 2030) costs in Belfast

Fig. 4. Annualised (year 2019 and 2030) private and external costs for six scenarios, from the usage of MGO and SSE in Dublin and Belfast.

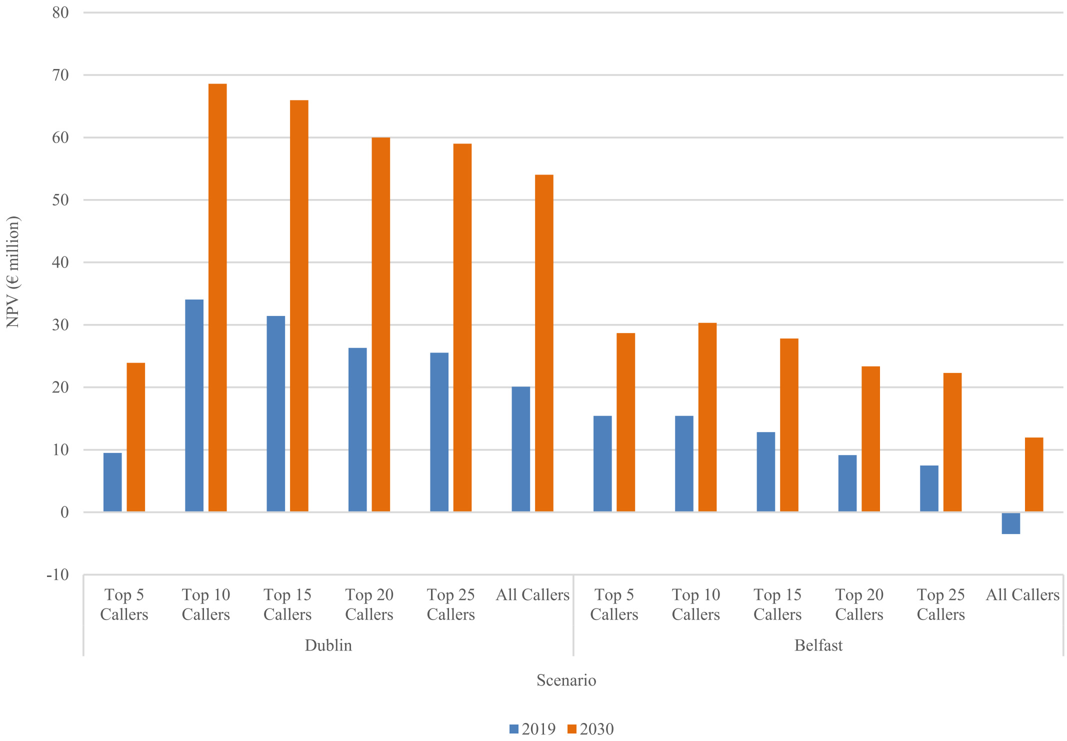


Fig. 5. 10-year NPV for six scenarios of SSE usage in Dublin and Belfast, based on year 2019 and year 2030 cost estimates.

renewable sources might be decorrelated from geo-political situations, prices do fluctuate as well, depending on weather conditions (Energia, 2022). Hence, the viability of using SSE (in current or future years) will depend on the evolution in electricity and fuel prices. Considering such uncertainties, a sensitivity analysis was provided to determine any changes in the NPV for the optimal scenario (SSE for top 10 callers).

With regards to the reliability of the calculated emissions, significant efforts were made to obtain precise data on ship activities while at berth using the AIS database. Information on issues such as engine and fuel type profiles, load factors, specific fuel consumption and emission factors are based on numerous assumptions which, while were obtained from high quality sources, may have some inherent variation. In the case of external cost estimation, the cost factors used have been widely applied in the literature and an attempt was made to localise the cost factors as much as possible.

5. Conclusion

The present study contributes to the existing literature by examining the costs and benefits of adopting SSE at varying levels of implementation, when considering the present (year 2019) and future (year 2030) Irish energy mix. To achieve this, we performed a cost-benefit analysis of introducing SSE, assimilating the port-side and ship-side private costs with the benefits achieved through reduced socio-environmental external costs and saved fuel costs, across six scenarios in Dublin and Belfast ports, using the NPV methodology. This is also the first study which investigated the potential use of SSE in Ireland.

The selection of Dublin and Belfast was primarily due to their higher population levels, while the impetus for selecting passenger ships was based on their proven energy demands while berthing and their significance to the Irish maritime economy. As of 2019, the composition of the Irish energy mix in electricity production is 62.43% non-renewable and 37.57% renewable, but it is expected to change to 20% non-renewable and 80% renewable, by 2030. For the 2019 grid supply, the use of SSE seemed viable for the top 5, 10, 15, 20 and 25 most frequently calling passenger ships, for both Dublin and Belfast ports. While switching all passenger ships to SSE in Dublin was feasible, the same was not the case for Belfast, due to higher private (mainly ship-side retrofit) costs. Switching to the year 2030 grid supply is expected to boost the obtained NPVs by 50%. Overall, the most profitable scenario by NPV was the implementation of SSE for the top 10 callers in Dublin and Belfast. From the sensitivity analysis carried out for this scenario, it was shown that unless there is an increase in the year 2019 electricity price by 90% (for Dublin) and 100% (for Belfast), the NPVs will remain positive. Furthermore, significant changes in the fuel prices, and 2030 electricity price, are not expected to impact the respective NPVs negatively.

The methodological framework proposed in this research is applicable for other port cities that wish to explore the potential of SSE, particularly in Europe, where there are similar profiles in terms of visiting ship types and a prevalence of urban ports. Future studies can also expand the proposed framework to other ship types (e.g., bulkers, containers, general cargo) to determine the viability of using SSE with current and future energy mix, on a wider scale.

Credit authors statement

Ketan Gore: Conceptualization, Methodology, Formal Analysis, Investigation, Writing – Original Draft, **Patrick Rigot-Müller:** Conceptualization, Methodology, Resources, Writing – Review & Editing, Supervision, Visualization, **Joseph Coughlan:** Writing – Review & Editing, Supervision, Visualization.

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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.

(a) NPV sensitivity of top 10 callers to electricity price variation

(b) NPV sensitivity of top 10 callers to fuel price variation

Fig. 6. NPV sensitivity of top 10 Dublin and Belfast callers to electricity and fuel price variation.

Data availability

I have mentioned the datasets used as references in the manuscript

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2022.116755.

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