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Shore power deployment strategies and policies including alternative fuels☆

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A R T I C L E I N F O

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A B S T R A C T

This study presents a novel evaluation framework to compare and optimize shore power deployment policies across shipping networks. The framework considers a wide range of policy instruments, including incentives, emission reduction regulations, and public funding. In addition to assessing the business case for shore power adoption, it incorporates the influence of alternative fuels and their implications for deployment strategies, offering a more holistic approach than previous models have suggested.

A test case on the St. Lawrence and Great Lakes dry and liquid cargo shipping network illustrates the framework's application for policymakers. Under appropriate policies, shore power could cover 30–50% of vessels' berth energy use. Achieving large-scale adoption would require an estimated government investment of $257 million USD in infrastructure. With projected cost savings of $240 million USD in external costs and a cumulative reduction of 2,556 kilotons of carbon dioxide equivalent by 2040, this scenario represents the most compelling policy option.

1. Introduction

The reduction of emissions in ports is a critical aspect of global environmental policies. Shore power, also called cold ironing or onshore power supply, enables ships to connect to the local electric grid and deactivate their auxiliary engines while at berth. A shore power connection generally consists of a shore-based electrical substation to distribute power to one or multiple berths, a cable management system to supply the ship with electricity, and other pieces of equipment on the ship and on shore to ensure the system follows international standards. When a ship or a berth has installed a shore power system, it is said that the ship or the berth is shore power capable.

Shore power leads to notable reductions in emissions such as carbon dioxide equivalents (CO_2e), nitrogen oxides (NO_x), sulphur oxides (SO_x), particulate matter (PM), etc. This reduction in harmful pollutants has proven benefits for public health, particularly in mitigating respiratory issues among communities near busy ports. The California shore power program, for instance, was largely driven by the need to improve local air quality and has become a model for similar initiatives globally. Today, the technology is well-established, making its implementation a relatively low-risk investment despite the upfront costs and compatibility challenges with

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certain vessel types. Furthermore, with increasing focus on reducing greenhouse gas emissions, especially in regions like the EU and China, shore power is gaining renewed attention as a critical component of sustainable maritime operations.

However, recent developments in shore power implementation indicate that governmental policies play a crucial role in its successful deployment. Furthermore, shore power deployment has been limited to specific ship types and regions, with dry and liquid carriers largely overlooked on a global scale.

Therefore, there is an urgent need to address and evaluate shore power deployment strategies and pathways to ensure efficient future expansion of shore power globally. To achieve this, policies, subsidies, incentives, and regulations must be analyzed to forecast shore power adoption under varying conditions.

1.1. Aim and contributions

This study aims to develop a comprehensive framework to evaluate how the different shore power policies affect its adoption, emissions and costs on a given shipping network. The framework provides policymakers, shipowners, and port authorities with data-driven insights for informed decision-making. A real-world application is presented for the dry and liquid cargo shipping network of the St. Lawrence and Great Lakes as detailed in (Daniel et al., 2024).

The key contributions of this study include:

1) Policy-comparison framework for shore power deployment

A modelling framework is presented that links berth electrification decisions, ship shore power integration and policy levers (investment subsidies, utilization subsidies, carbon taxes, regulations, etc.) across a multi-port network. This enables assessment of system-wide impacts and identification of policy interactions that, while beneficial at a local scale, may produce suboptimal outcomes at the network level if considered separately. The model can be used with any ship type and shipping network.

2) Explicit integration of alternative fuel adoption

Competition between shore power and alternative fuels (e.g., electricity, marine biofuels, e-fuels, etc.) is represented under price uncertainty. Including alternative fuels yields a more realistic assessment of deployment pathways and prevents misleading policy recommendations that would follow from single-pathway analyses only focused on shore power.

3) Application to a real network: St. Lawrence and Great Lakes dry and liquid cargo shipping

This work provides real-world results on an existing shipping network, and delivers policy recommendations and pathways toward shore power deployment.

4) Policy insights and forecasting

Scenario and game theory is used to compare policy alternatives and generate forecasts of policy outcomes under plausible future pathways. It provides policymakers with insights for policy design, including priority berths, subsidy targeting, and likely system-wide impacts.

The following sections address the background and foundations of shore power deployment strategies and their relationship with alternative fuels.

1.2. Literature review

Shipping decarbonization is being addressed through five levers including: policy and regulations, technological advancements on ships, energy and fuel advancements, customer demand and pull, and finance sector mobilization. Shore power regulations are generally part of governmental policies and may include provisions that allow ships to avoid connecting to shore power if they employ an equivalent zero-emission technology. Also, many countries do not yet have a shore power regulation. Therefore, shore power can enter into competition with alternative fuels to comply with zero-emission goals. Faber *et al.* (Faber and Berg, 2023) addressed the role of shore power in the future energy mix by comparing the predicted average future cost of electricity (USD 0.01–0.23/kWh) to the predicted future cost of electricity generated by ammonia onboard ships (USD 0.20–0.33/kWh). They concluded that shore power should be more competitive in the long run. However, the wide range of possible future costs introduces significant uncertainty, which means these projections should be interpreted with caution.

To address shore power competitiveness compared to alternative fuels, the literature review investigates the future costs of alternative fuels and electricity, followed by a detailed review of shore power deployment policies.

1.2.1. Future costs of alternative fuels and electricity

It is impossible to accurately predict future fuel or electrical costs, but it is possible to estimate the production cost, which has an important influence on the future cost. The alternative fuels are generally separated into different categories: the ones that are derived from a feedstock (biofuels), the fuels generated with electricity (e-Fuels), and the low-carbon fuels, such as liquified natural gas

(Fossil). Table 1 summarizes the estimated future equivalent cost of alternative fuels and electrical cost.

The results summarized in Table 1 indicate that even with environmental regulations in place, fossil fuels will continue to outcompete alternative fuels for the foreseeable future. In the best scenario, there may be a few e-Fuels or biofuel types that might compete in cost with fossil fuels. However, they may not be readily available and may likely have wide ranges in costs up to ten times the cost of fossil fuels.

Electricity, on the other hand, has a much lower cost of production. However, the final cost of electricity is always subject to the spot market and other fees such as distribution, maintenance, etc. The EPA work (US EPA, 2022) reports that US ports' shore power cost is between $0.056/kWh and $0.26/kWh. In China, the shore power cost is between $0.15/kWh and $0.47/kWh (Mirza, 2022).

Therefore, the competitiveness of shore power compared to alternative fuels is highly complex, region-based, and fuel-based. To account for such a large cost difference, a very large range of prices must be considered. Given that fossil fuels will most likely outcompete other alternative fuels, shore power policies are required to enable its deployment.

1.2.2. Shore power deployment policies

Shore power is a multidisciplinary research topic encompassing technical, economic, and policy aspects. Wang *et al.* (Wang et al., 2024) identified shore power's technical aspects as the earliest sub-research topic that was explored. Subsequently, research expanded to include harbour emissions and energy demand. Recently, the research has started to shift to policies and shore power deployment. The review concludes that the primary drivers for shore power adoption are regulatory mandates, incentives, and government subsidies in California, Europe, and China.

Various shore power policies exist and can generally be classified into two categories: regulatory and market-based. However, the number of governmental policies worldwide enforcing or promoting shore power is limited, and they are not generally backed by a precise methodology. Few studies provide a comprehensive review of these policies. For example, (Selén, 2023) analyzes EU policies, while (Yin et al., 2020) and (Wang, 2024) focus on Chinese regulations. Key challenges to shore power adoption include high investment costs, low returns on investment, standardization difficulties, and slow installation rates of shore power facilities.

As discussed, the deployment of shore power is complex, and some contributions have investigated the issue under the name of the shore power deployment problem (SPDP). L. Wang *et al.* (Wang et al., 2021) proposed a bilevel economic approach working with regulators at the upper level and the ports at the lower levels. The goal of the regulators is to minimize at-berth emissions with subsidies and taxes, while the goal of the ports is to minimize the cost of emission control. In (Wu and Wang, 2020), the authors assessed the SPDP by developing a subsidy program that could achieve the most greenhouse gas (GHG) reductions for container shipping. The model is flexible and evolutive since subsidies to ports and shipowners will affect each other: more ports converted to shore power will bring more ships to be converted to shore power, and the same with ships for ports. After having proven that the problem was NP-hard, the authors chose a labelling algorithm to solve the problem. However, the model assumes a pre-existing set of ships and berths equipped with shore power, a condition that does not always reflect real-world shipping networks. In (Vaishnav et al., 2016), a large data analysis of 46,000 unique calls, 3300 unique ships and 187 unique U.S. ports determined the best way to implement

Table 1
Predicted cost of alternative fuels in 2025 USD, fossil fuels, and electrical production cost.

Year	2020	2025	2030	2040
Alternative fuels ($ per ton of very low sulphur oil)				
(Solakivi et al., 2022), *production cost*				
Biofuels	882–2,491		911–2,788	911–3,072
e-Fuels	2,645–8,352		2,144–5,603	1280–4,202
Fossil	185–908		268–1,259	288–1,410
(Li et al., 2022), *minimum fuel selling price*				
Biofuels	751–1,779			
(Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2025)				
Biofuels		940–1,485	886–1,262	786–1,118
e-Fuels		2211–4,474	1,697–3,782	1,420–2,993
Fossil		378–799	465–535	469–567
(Sustainable Ships, 2025), *including FuelEU and EU ETS*				
Biofuels		993–1,825	1,046–1,836	1,165–2,081
e-Fuels		1,212–1,804	1,319–1,806	1,536–1,844
Fossil		680	765	1,488
(MEPC, 2023), *percentage of very low sulphur oil cost*				
Biofuels		150 %-158 %	102 %-155 %	134 %-207 %
e-Fuels		100 %-393 %	125 %-274 %	108 %-254 %
Fossil		100 %	100 %	100 %
(Rutherford et al., 2024)				
Biofuels			1,180–3,314	1,180–3,159
e-Fuels			2,809–4,683	2,339–3,958
Electricity ($ per kWh)				
(IEA, 2025)	0.007–0.075	0.023–0.166		
(Government of Canada, 2023), *wind and solar*	0.024–0.067	0.023–0.057	0.021–0.047	0.019–0.033
(IEA, 2021)	0.089		0.011	0.101
(De Vita et al., 2021), *industrial price*		0.221	0.226	0.228

shore power in California's main ports. They developed a model that estimates maximum private benefits and total benefits, which aggregates private benefits and social benefits. The GUROBI solver was used to solve the mixed integer linear program. The results show that subsidies are required the get most of the societal benefits of shore power. An issue with the analysis is that it treats all berths as a whole, whereas individual berth visits must be addressed on a case-by-case basis. The shore power implementation model presented in (Song et al., 2017) is well-defined and can effectively estimate shore power costs. However, the model was mostly used to determine the share of governmental incentives that shore power projects should receive.

Huang *et al.* (Huang et al., 2023) propose a two-stage dynamic game model based on port shore power investment to optimize shore power renovation projects. However, their model focuses exclusively on the shore-side infrastructure. Lu *et al.* (Lu et al., 2024) investigate the optimal shore power adoption rate in a network of two ports, including multiple economic factors and use the Hotelling algorithm to solve the game theory model. They found that a port with lower service quality can increase its competitive advantage by supplying shore power, and that only significant governmental funding could enable full shore power deployment. In (Du et al., 2024), Du *et al.* investigated the factors influencing shore power adoption in bulk terminals and tramp shipping networks. With a real-world model of 20 ports and 12 Panamax ships, they found that improving the loading and unloading time by more than 40 % could have negative impacts on shore power adoption. They also found that efficiency improvements do not necessarily lead to emission reductions, as shore power deployment would be limited. Finally, they emphasize the importance of analyzing multiple carbon reduction policies concurrently to prevent potential conflicts. Finally, Merkel *et al.* (Merkel et al., 2023) studied the economics of non-linear shipping shore power access. Using an investment appraisal framework, they managed to model non-linear routes for tanker ships, container ships, and bulk carriers. The results indicate that the provision of shore power to the studied ship types can provide socio-economic benefits with adequate access pricing. However, the results also indicate that a network-wide mandate of shore power for bulk carriers would come at a very high cost.

Tan *et al.* (Tan et al., 2025) addressed the shore power capacity allocation problem in a container shipping network, considering the strategic equilibrium of ship service selection. They developed an exact method to determine the capacity levels for multiple ports, ensuring emission reductions under governmental financial support conditions. Their study shows that misallocating shore power capacity can paradoxically increase port emissions because of port congestion. Wang *et al.* (Wang et al., 2025) developed game theory models for policymakers to analyze shore power strategies, examining interactions among governments, port operators, and shipping companies under different policy scenarios, including non-intervention, emission taxes, and subsidies. A container terminal case study at Nanjing Port's Longtan Harbour in China revealed that subsidy policies outperform emission taxes and non-intervention in achieving optimal socio-economic benefits. Using a Stackelberg game framework, Peng *et al.* (Peng et al., 2023) analyzed government subsidies for shore power, comparing facility investment and price-based strategies. They found that price-based subsidies are more cost-effective when budgets are constrained, and the marginal benefit of emission reduction is high. Carbon leakage, understood as the displacement of emissions outside a regulated jurisdiction, was examined by (Peng et al., 2025) in the case of shore power policies under Quebec's regional emission trading system. The authors recommend increased government and port investment in shore power infrastructure to mitigate this risk and support the effective implementation of market-based measures.

Other studies also assess the deployment of shore power without providing a decision-making process about the electrification of the berths. The case of Aberdeen shows that it is feasible to install shore power in medium-sized ports (Innes and Monios, 2018). The paper provides very detailed insights into berth and port electrification. However, the authors decided to electrify all berths, neglecting the cost-benefit analysis of different scenarios. Similarly, the Port of Gävle study (Gutierrez Saenz, 2019) did a similar decision process by only electrifying the 12 ships that were occupying the port's berths for ~ 90 % of the time. While this decision was easier to make because of the small number of ships spending a long time in port, not all ports have this advantage.

Table 2 provides an overview of research on shore power deployment, detailing the model architecture used and whether studies address key aspects: economic, environmental, social, or alternative solutions to shore power (✓ for yes, ≡ for no). "Terminal Type" specifies ship types covered, and "Policy" categorizes measures as market-based (U = Utilization subsidy, I = Investment subsidy) or regulatory (M = Mandatory).

In summary, the literature shows that shore power for tramp shipping can provide important social and economic benefits if it is correctly supported by policies. However, only small-scale models have been used, and bulk carriers are only represented in a small number of studies. Larger networks should be considered to enable precise evaluation of tramp shipping shore power policies' costs and benefits.

Most articles assess the economic aspect and emissions reductions, but fail to account for broader environmental policies or their relationship with alternative solutions like alternative fuels and a carbon tax. Indeed, none of the analyzed shore power papers integrated alternative fuels into their framework, which needs to be investigated. Policy analysis predominantly focuses on utilization and investment subsidies but generally lacks an integrated, long-term perspective, including all types of market-based and regulatory policies. Additionally, the cost of emissions in ports is not addressed in a consistent manner although it has profound implications on shore power economics. As an example, the California shore power program is entirely funded based on public welfare benefits (US EPA, 2022).

Furthermore, the literature highlights the fact that multiple policies and factors must be considered at the same time when investigating shore power policy.

To address these limitations, future research about shore power deployment for the bulk shipping segment of the maritime industry should incorporate alternative fuels, expand model sophistication and scale, and evaluate policies holistically to enable a more precise and comprehensive assessment of shore power's costs and benefits.

The remainder of this paper is structured as follows: Section 2 outlines the methodology, Section 3 presents and analyzes the results

Table 2
Summary of the shore power deployment research articles.

Article	Model	Economic	Environmental	Social	Shore power alternatives	Terminal types	Policy
(Wang et al., 2021)	Mixed integer bilevel programming model	✓	✓	≡	≡	Not specified	U, I
(Wu and Wang, 2020)	Labeling algorithm	✓	✓	≡	≡	Container	I
(Vaishnav et al., 2016)	Mixed-integer linear problems	✓	✓	✓	≡	Cargo vessels and cruise	NA
(Song et al., 2017)	Economic optimum principle	✓	✓	✓	≡	Not specified	I
(Huang et al., 2023)	Two-Stage Dynamic Game	✓	✓	≡	≡	Not specified	I
(Lu et al., 2024)	Two-stage game model	✓	✓	✓	≡	Not specified	U
(Du et al., 2024)	Mixed-integer nonlinear programming model	✓	✓	≡	≡	Bulk carrier	U
(Merkel et al., 2023)	Investment appraisal model	✓	✓	✓	≡	Bulk carrier, general cargo, tanker, container	NA
(Innes and Monios, 2018)	Cost-benefit analysis, quantitative research	≡	✓	✓	≡	Offshore supply vessel, ferry	I
(Gutierrez Saenz, 2019)	Economic analysis	✓	✓	≡	≡	Cargo and passenger carriers	NA
(Tan et al., 2025)	Equilibrium choice	✓	✓	✓	≡	Container	U, I
(Wang et al., 2025)	Game theory	✓	✓	≡	≡	Container	M, U, I
(Peng et al., 2023)	Stackelberg game	✓	✓	✓	≡	Not specified	U, I
(Peng et al., 2025)	Dynamic model simulation	✓	✓	≡	≡	Container	M, I

Table 3
Summary of the shore power policies covered by the study.

Policy	Policy category	Policy type	Description
Business-as-usual	NA	NA	The government takes no action toward shore power.
Carbon tax (C_{tax})		P	Additional governmental tax on the price of carbon equivalent emissions.
Zero-emission regulation (ZE_{reg})		M, P	Ships are required to eliminate their emissions at berth. Penalty applied to all emissions occurring at berth.
Shore power usage regulation (SP_{reg})		M, P	Penalty applied to ships/ports not connecting to shore power when capable.
Electrical price incentive (E_{incent})		U	Governmental subsidy on the cost of electricity for shore power.
Port incentive (P_{incent})		U	Port financial incentive for ships connecting to shore power.
Full funding policy (F_{full})		I	Governmental subsidy covering the entire cost of shore power investments.
Strategic funding policy (F_{strat})		I	Governmental subsidy covering the berths and ships with the best emission reduction potential.

of the test case, and Section 4 summarizes key findings.

2. Methods and materials

Based on the literature review and the problem description, different regulatory and market-based policies are explored in this work. Table 3 summarizes these policies and differentiates them between the market-based measures ( ), and the regulatory measures ( ). The policy type is also represented by U = Utilization subsidy, I = Investment subsidy, P = Penalty, and M = Mandatory measures. A high-level description follows below.

In addition to the policies studied, the model incorporates variations based on economic assumptions regarding future alternative fuels at berth during the period in which funding is applicable, and the funding share. This study investigates the case of biofuels as they are considered by the industry to reduce shipping emissions in the St. Lawrence and Great Lakes (IMAR and Great Lakes St. Lawrence Governors & Premiers, 2022). However, as detailed in the literature review, the competitiveness of alternative fuels compared to shore power is a question of fuel cost, electricity cost, and regulation. Therefore, the results of this study are also applicable to any alternative fuels that can be used directly in the auxiliary engines. The alternative fuels that cannot be used directly are more complex to compare because the complexity of the capital expenditure increase is not covered.[1]

The analysis of each policy, economic assumption, and combination of policies and economic assumptions leads to a large number of scenarios. Eleven realistic scenarios have been selected based on Table 3 and are detailed in Appendix B along with additional modifications to the general model presented subsequently.

To estimate the impact of environmental policies on the shore power network, a game-theory model combined with scenario analysis is developed and detailed in the next sections.

2.1. Main model

The model starts from the basic principle that if shore power is less expensive than other possibilities, the shipowners and the ports will invest in retrofitting or installing it on new ships and new berths. Each year, the economics of shore power are addressed by the stakeholders by repeating the six steps of Fig. 1.

First, the yearly total operational costs C_{sOPtot} for each ship are estimated in eq. (1) by aggregating the operational cost $C_{OP\ AE}$ of each ship stays *st*, i.e., each port calls in *ST*, and fuel *f* for all fuels *F*.

$$C_{sOPtot(s,y)} = \sum_{f \in F} \sum_{st \in ST} C_{OP\ AE(f,st,y)} \tag{1}$$

Second, the potential operational shore power costs for ships $P_{sOP\ SPtot}$ and for berths $P_{bOP\ SPtot}$ are also measured in eq. (2) and eq. (3) for each case where the ship or the berth could use or supply shore power.

$$P_{sOP\ SPtot(s,y)} = \sum_{st \in ST_{(s_{SP})}} P_{OP\ SP(st,y)} \tag{2}$$

$$P_{bOP\ SPtot(b,y)} = \sum_{st \in ST_{(b_{SP})}} \left(P_{OP\ SP(st,y)} + P_{In\ SP(st,y)} \right) \tag{3}$$

where $P_{OP\ SP}$ is the potential cost of shore power for a ship stay in port, $P_{In\ SP}$ is the potential shore power income for the port set to USD $2,000 per ship stay in port.

Third, the annualized investment of shore power I_{SP} is calculated in eq. (4) and eq. (5) using an interest rate i_r of 6 % and a lifespan *Y* of 25 years. Typically, the investment cost is significantly lower for new buildings and new construction compared to retrofits, as shore power can be integrated into the initial plans. Retrofits require modifying the actual installations, which means more work, extended modifications and more resources. For this reason, it is estimated that if a ship attains the theoretical maximum lifespan of 25 years, the ship will be replaced with an equivalent ship with the possibility of installing shore power at a smaller cost. The only exception is for domestic ships sailing in the St. Lawrence and Great Lakes as they tend to have a very long lifespan. Also, because berths can have a very long lifespan and because it is impossible with the available data to determine consistently when a berth will be rebuilt, the berth shore power investment cost is always the same.

There are multiple works including cost estimation for shore power conversion on vessels. The Salish Sea report estimates the shore power cost on new buildings to be between USD $50,000 and $750,000 per vessel. For retrofits, the cost of containerships can vary between USD $268,500 and $2,146,500 (Billings et al., 2022). The cost of retrofitting a ship to shore power is estimated to $680 k and $2 M for a berth in 2025 USD based on (Vaishnav et al., 2016). Different market reports also state that the difference between the retrofit cost can be up to twice higher than the newbuilding cost (PW Consulting, 2025). Based on these numbers and on discussions with stakeholders of the industry of the St. Lawrence and Great Lakes dry and liquid shipping network, the cost of shore power

[1] It could be argued that even alternative fuels requiring main engine and auxiliary engine upgrades could be covered by this methodology because the decision to invest in the upgrades is not in competition with the shore power investment. Indeed, the decision to perform the upgrades for alternative fuels will be based on the sea going emissions mainly while the shore power *usage* is in competition with the at-berth emissions.

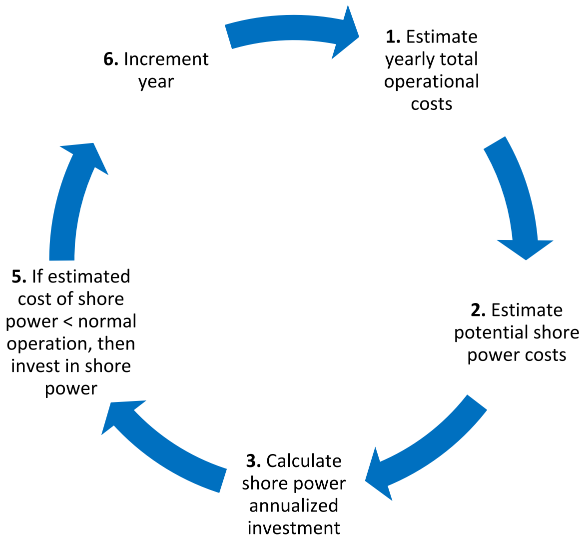

Fig. 1. Annual shore power investment loop.

conversion was estimated to be USD $250,000 for newbuilds and USD $750,000 for retrofits in this study.

$$I_{SPs(s,y)} = \begin{cases} C_{NewBuilding_s} \times i_r/(1-(1+i_r)^{-Y}), & if\, y = Y_s \wedge Type_{(s)} \neq Domestic \\ C_{Retrofit_s} \times i_r/(1-(1+i_r)^{-Y}), & Otherwise \end{cases} \quad (4)$$

$$I_{SPb(b,y)} = C_{retrofit_b} \times i_r/(1-(1+i_r)^{-Y}) \quad (5)$$

where $C_{NewBuilding}$ is the investment cost of a new ship, and $C_{Retrofit}$ is the cost of a shore power conversion, i.e., a retrofit.

The fourth step is a decision. If the cost of the shore power investment and potential operational cost is smaller than the cost of using the auxiliary engines, the investment is performed for the next year. The logical equation for shore power investment is presented in (6) for the ships and (7) for the berths. Finally, the yearly loop of Fig. 1 is repeated annually till the end of the simulation time.

$$SP_{s(s,y)} = \begin{cases} 0, & if\, C_{OPtot(s,y)} < I_{SP(s,y)} + P_{OP\,SPtot(s,y)} \\ 1, & Otherwise \end{cases} \quad (6)$$

$$SP_{b(b,y)} = \begin{cases} 0, & if\, C_{OP\,Ntot(b,y)} < I_{SP(b,y)} + C_{OP\,SPtot(b,y)} \\ 1, & Otherwise \end{cases} \quad (7)$$

With the first blocks of the mathematical model in place, the next sections detail the decision process for a ship to use one of the different types of energies at berth, and how the policies can change the economics of shore power at berth.

2.2. Energy use

Before Fig. 1′s yearly loop where operational costs are aggregated, they need to be estimated. Each time a ship enters a port, it faces an economic decision which is depicted in Fig. 2.

When a ship arrives at a port, one of four scenarios can occur: (1) both the ship and the port are shore power capable, (2) only the ship has shore power capability, (3) only the berth is shore power capable, or (4) neither has shore power capabilities. In all cases, the ship will perform an economic estimation of the energy cost based on the electricity cost, fuel cost, regulation penalties, etc. Based on its estimation, the ship selects the cheapest energy between shore power if possible, marine diesel oil (MDO), or biofuels if available. An extensive energy use decision flowchart is provided in Appendix B in complement to this explanation.

The first case is the only one where a shore power connection might happen. In the second case, where only the ship is shore power capable, the energy decision is between MDO and biofuels if available. Also, the berth might get penalties if it does not invest in shore power to comply with regulations. In the third case, it is the ship that might get penalties if it does not comply with regulations. In the last case, both the ship and the berth might be charged with penalties.

To determine the energy cost, estimations must be made as it is impossible to predict the future cost of fuel and electricity. Khuntia *et al.* (Khuntia et al., 2016) suggest using scenario analysis to counter the issue. As detailed by H. Kosow and G. Robert (Kosow and Robert, 2008), a scenario includes a possible window into the future, which is used to illustrate how uncertainties widen over time. Therefore, the model uses two combinations of fuel cost and electricity cost which provide a window of possibility for each investigated scenario, i.e., a high penetration case of shore power (H) and a low penetration case of shore power (L) as summarised in Table 4. The first combination is a high cost of electricity coupled with a low cost of fuel. In this case, shore power has less chance to be used as

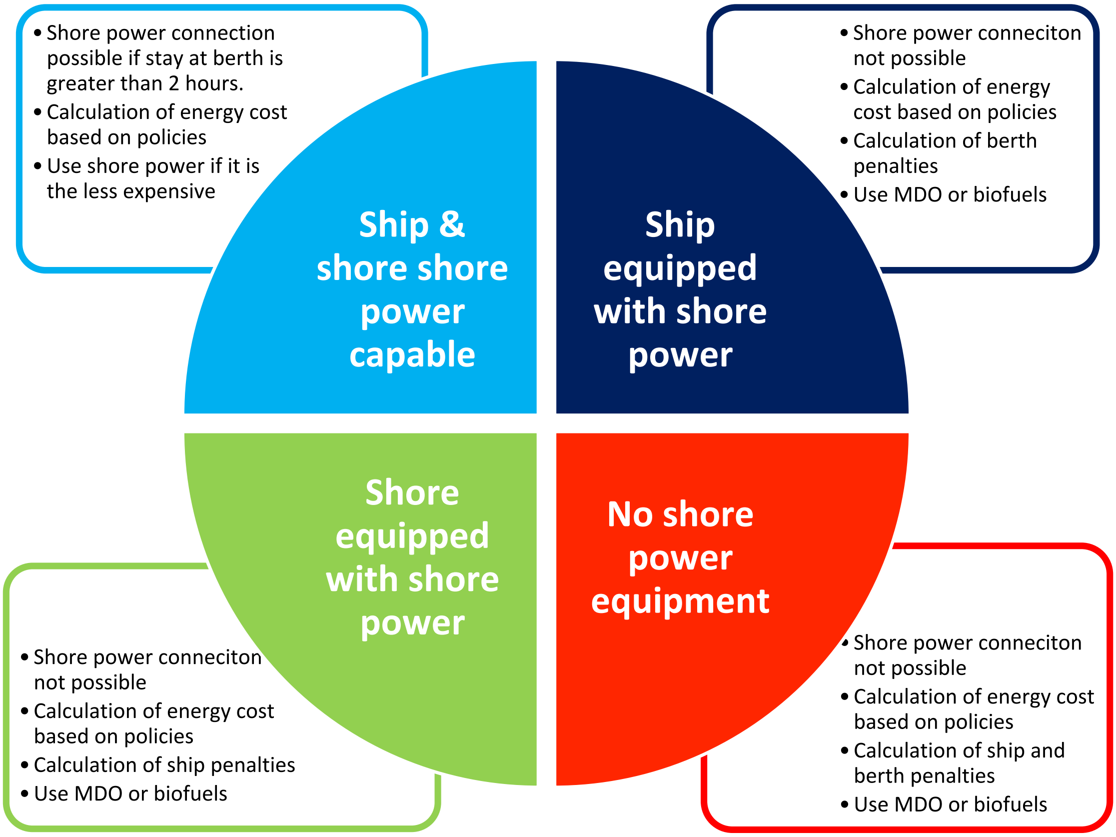

Fig. 2. Energy use matrix.

operating the auxiliary engines is less expensive. In the second combination, a low cost of electricity is coupled with a high cost of fuel, providing the best outcomes for shore power because the shore power operational cost will be less than the use of the ship's auxiliary engines. The fuel cost is based on the average fuel cost in the Seaway over the past 10 years.

Then, the cost of using the auxiliary engines at berth also includes equipment usage. When shore power is operational and connected, all the ship's engines are shut making it easy for the crew to perform maintenance tasks. When the auxiliary engines are working, all their running hours are counted, and after about a year of running time, they need to have a major maintenance. Therefore, (8) is the operational cost of running the auxiliary engines for a ship stay in port, i.e., a port call *st*:

$$C_{OP\ DG(f,st)} = FC_{(st)} \times C_{fuel(f)} + 1.5 \times TIP_{(st)} \times C_{RH} \tag{8}$$

In (8), the fuel consumption *FC* is multiplied by the fuel cost C_{fuel} for the fuel *f*, and the time in port of the ship *TIP* in hours is multiplied by the cost per hour of running the auxiliary engines C_{RH}. Since dry and liquid cargo ships often operate two auxiliary engines simultaneously in port, a 150 %-time factor is applied to the cost of generator use, accounting for the additional running hours. This assumption adds 50 % more operating time to reflect the second generator's usage.

When a ship is using shore power, the operational cost is presented in (9). However, the auxiliary engines of the ship are still used during the connection and disconnection time estimated to be 45 min for each operation based on (IMAR, 2022). In addition to the electrical consumption *EC* and the electricity cost C_{elec}, there is also the cost of connecting and disconnecting the ship C_{conn}:

$$C_{sOP\ SP(st)} = EC_{st} \times C_{elec} + C_{conn} \tag{9}$$

Table 5 summarizes the base operational costs considered in this study for using shore power on a ship versus generating electricity

Table 4
Window of possibility, boundaries definition.

Window of possibility boundary	Definition	Cost assumption (USD)
High penetration boundary (H)	• The high penetration case happens when the fuel cost is high, and the electricity cost is low. • In this case, it is more economical to use electricity instead of fuel at berth	• Fuel: \$1000/t • Electricity: \$0.10/kWh
Low penetration boundary (L)	• The low penetration case happens when the fuel cost is low, and the electricity cost is high. • In this case, it is generally more economical to use fuel instead of electricity at berth.	• Fuel: \$600/t • Electricity: \$0.35/kWh

without any policies.

2.3. External costs and emissions

While the choice to invest in shore power is purely an economic decision, the ranking of the best policy is made with the total emissions that can be reduced in terms of GHG and air pollutants. To compare each scenario on the same basis, the external costs' monetary value is selected as the main indicator. External costs can show the benefits of reducing multiple emission types with only one indicator. Indeed, external costs are an aggregation of the cost of GHGs in environmental disasters and infrastructure adaptation, the costs on the healthcare system and for society resulting from air pollutant emissions, and the costs of premature deaths. Indeed, scenarios with biofuels can technically reduce GHG emissions to a value that is close to zero, which would make it hard to compare scenarios with each other only on the basis of GHG reductions. Using the external cost value for each type of emissions makes it possible to compare all scenarios on the same basis.

External costs are calculated using models and software that consider factors such as geographical location and population density. In the maritime context, pollutants like carbon dioxide (CO_2), nitric oxides (NO_x), sulphur oxides (SO_x), and particulate matter (PM) are attributed an external cost per ton, reflecting their adverse impacts on public health, such as respiratory issues, and ecosystems, including crop and biodiversity losses.

For instance, Environment and Climate Change Canada (ECCC, 2019) sets the social cost of CO_2 at CAD $50 per ton, a figure that also applies to CO_2e emissions. Health Canada (HC, 2022) has provided a detailed analysis of the external costs of air pollutants for specific regions, though its scope is limited to on-road and industrial sectors in defined corridors. Consequently, approximate estimations for maritime external costs are adopted: CAD $380,000 per ton for PM, CAD $4,900 per ton for NO_x, and CAD $10,000 per ton for SO_x.

2.4. Assumptions

To complete the formulation of the model, some assumptions have been made to enable a realistic simulation of the shore power network of the St. Lawrence and Great Lakes. First, data from (Daniel et al., 2024) has been taken as input for the port calls in the shipping network. The database encompasses five years of port calls along with the estimated electrical demand, emissions, external costs, etc. To simulate the network, it is assumed that the five-year pattern is repeated until the end of the simulation with the mathematical model previously detailed. Also, the source data includes the electrical consumption of the boilers. Therefore, it is assumed that ships will invest in electrical boilers to reduce their emissions completely while using shore power. Then, having shore power does not provide any competitive advantage or disadvantage outside of the economic model of Section 2. Finally, the model considers that shore power is only driven by the St. Lawrence and Great Lakes policies, meaning no international ships are previously equipped with shore power.

3. Results and discussions

The model was applied to the dry and liquid cargo shipping network of the St. Lawrence and Great Lakes studied in (Daniel et al., 2024), with projections extending until 2040. This section provides a high-level analysis of shore power deployment across various scenarios and is followed by a section on the abatement cost of the different scenarios.

3.1. Shore power deployment

Fig. 3 presents the external costs of ships' emissions at berth, on the y-axis, as a function of the years, on the x-axis, for each scenario. Each scenario under investigation, as detailed in the methodology section, is plotted with an average curve and a window of

Table 5
Summary of the base operational costs.

Item	Cost (USD)	Resulting cost of electricity (USD)	Assumptions
Auxiliary engines			
Fuel consumption	$600/t – $1,000/t	$0.11/kWh – $0.19/kWh	Specific fuel oil consumption of 185 g/kWh (Faber et al., 2020)
Auxiliary engines running time	$15/h (Knoke et al., 2003)	$0.03/kWh	Energy consumption at 80 % load for a single 600 kW auxiliary engine.
Total		$0.14/kWh – $0.22/kWh	
Shore power			
Electricity	$0.10/kWh-$0.35/kWh	$0.10/kWh – $0.35/kWh	–
Connection and disconnection	$1000 – $2000	$0.03/kWh – $0.06/kWh	While it is hard to find precise information about this fee, consulted experts in the field suggested this value. The conversion to $/kWh is based on the same assumption as the auxiliary engine and a typical port call duration of 3 days.
Total		$0.13/kWh – $0.41/kWh	

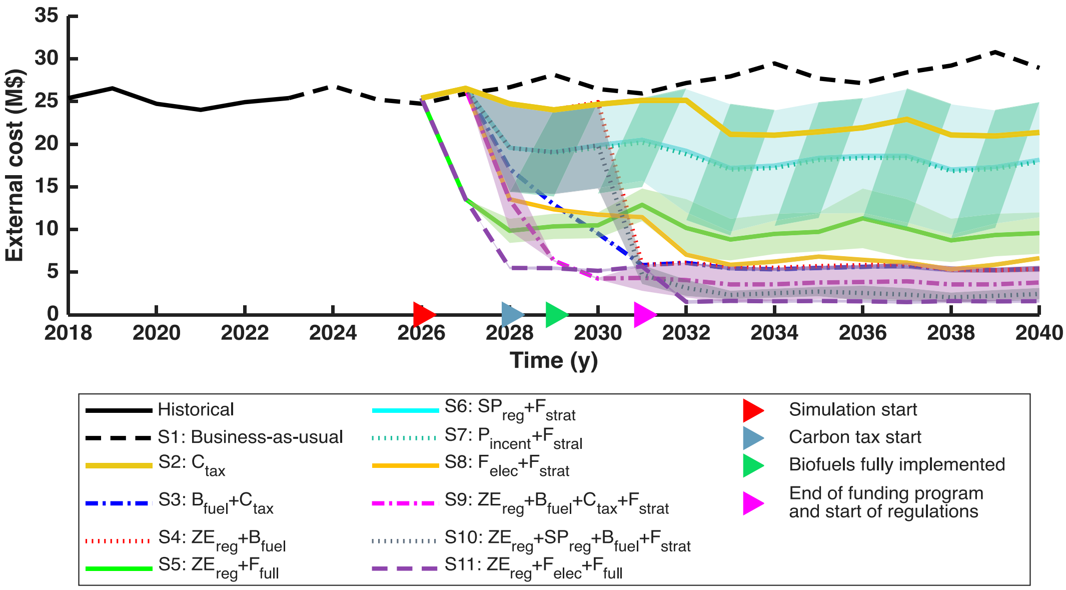

Fig. 3. Scenario analysis: Annual external costs.

possibility. The window of possibility is bounded by a high and a low shore power penetration case, as previously summarised in Table 4. All other cases fall within these boundaries, reflecting the uncertainty in future fuel and electricity costs. This assumption is detailed in Section 2.2. Finally, the right-pointing triangles of Fig. 3 indicate when milestones happen, and each scenario is represented by its number, i.e., scenario 1 is S1, scenario 2 is S2, and so on.

In the first scenario (S1), the emissions are slowly increasing, and there is no implementation of any environmental policies. As shore power represents an additional investment that is not economic when the air pollution and environmental costs are not considered, there is no implementation of shore power in the business-as-usual scenario. Also, a quick analysis of Fig. 3 indicates that the scenarios with the best reduction in external costs are S10 and S11.

In 2026, the simulation starts. Only scenarios S5 and S11 can diminish quickly and radically the external costs during the first years thanks to their full funding policy. In 2029, the alternative fuels bunkering infrastructure for biofuels is fully implemented, and 100 %

Table 6
Scenario analysis comparative table with the costs in USD.

Scenario	Scenario description	Case	F(%)	B(%)	E(%)	CO2 (kt)	External cost	Funding berths	Funding ships	Funding electricity	Penalties berth	Penalties ship	Total cost
S1	Business as usual	H	100%	0%	0%	3406	$377 M	0	0	0	0	0	$377 M
		L	100%	0%	0%	3406	$377 M	0	0	0	0	0	$377 M
S2	Carbon tax	H	92%	0%	8%	3129	$347 M	0	0	0	0	$5315 M	$5662 M
		L	92%	0%	8%	3133	$348 M	0	0	0	0	$5324 M	$5671 M
S3	Biofuels & carbon tax	H	22%	73%	6%	736	$145 M	0	0	0	0	$531 M	$676 M
		L	22%	78%	0%	736	$149 M	0	0	0	0	$532 M	$681 M
S4	Biofuels & zero-emission regulation	H	33%	64%	3%	1135	$181 M	0	0	0	0	0	$181 M
		L	33%	67%	0%	1135	$183 M	0	0	0	0	0	$183 M
S5	Zero-emission regulation & full funding	H	37%	0%	63%	1227	$139 M	$1630 M	$83 M	0	$1 M	0	$1852 M
		L	54%	0%	46%	1806	$201 M	$1630 M	$83 M	0	$1 M	0	$1914 M
S6	Shore power regulation & strategic funding	H	56%	0%	44%	1846	$210 M	$250 M	$8 M	0	0	0	$468 M
		L	100%	0%	0%	3400	$376 M	$250 M	$5 M	0	0	0	$631 M
S7	Port incentive & strategic funding	H	54%	0%	46%	1786	$203 M	$250 M	$13 M	0	0	0	$466 M
		L	100%	0%	0%	3406	$377 M	$250 M	$5 M	0	0	0	$632 M
S8	Electrical price incentive & strategic funding	H	41%	0%	59%	1350	$155 M	$250 M	$17 M	$2325 M	0	0	$2746 M
		L	42%	0%	58%	1396	$160 M	$250 M	$17 M	$2269 M	0	0	$2696 M
S9	Biofuels & Zero-emission regulation & strategic funding & carbon tax	H	18%	27%	55%	606	$90 M	$250 M	$16 M	0	0	$272 M	$629 M
		L	20%	74%	7%	667	$138 M	$250 M	$15 M	0	0	$394 M	$797 M
S10	Biofuels & shore power and zero-emission regulation & strategic funding	H	25%	23%	52%	850	$115 M	$250 M	$8 M	0	0	0	$373 M
		L	33%	40%	27%	1135	$160 M	$250 M	$5 M	0	0	0	$415 M
S11	Electrical price incentive & shore power and zero-emission regulation & full funding	H	19%	0%	81%	634	$73 M	$1630 M	$83 M	$3177 M	$1 M	0	$4962 M
		L	21%	0%	79%	677	$77 M	$1630 M	$83 M	$3124 M	$1 M	0	$4914 M

of the fuel consumed at berth is from shore power or alternative fuels in the related policies. Then, in 2031, the zero-emission and shore power regulations kick in after 5 years of preparation for ports and shipowners, driving a strong reduction of external costs for S4 and S10.

Table 5 provides a detailed comparison of energy use by type and scenario, CO2e emissions reductions, external costs, total funding, and penalties. The “Case” column refers to the window of possibility in Table 4.

On the first line of the table, the business-as-usual scenario is included as the reference. In 2040, the business-as-usual scenario will have cost USD $377 M in external costs and result in 3,406 kt of CO_2e by 2040.

The second scenario, S2, considers a carbon tax and results in USD $347 M of external costs. While this scenario is inexpensive for governments and ports, there is an important cost that is transmitted to shipowners. Most likely, however, it is a cost that will be indirectly paid by the end consumer as the cost of transportation will increase. The biggest strength of S2 is its capacity to ensure a reduction in external costs of 8 % as the difference between the high shore power penetration case and the low shore power penetration case is less than 1 %.

For the third scenario S3, biofuels can reduce an important share of the emissions and bring the external costs down to USD $147 M. In the best shore power penetration case, there is a small uptake of shore power, as 6 % of the energy could be supplied by shore electricity. Also, the carbon tax cost that is transferred to the shipowners in S3 is much smaller compared to S2. The fourth scenario S4 is similar to S3 with the difference that instead of using a carbon tax to drive emission reductions, a zero-emission regulation at berth is used. While the external costs and resulting emissions are a bit higher than the previous scenario, the penalty paid by ships is zero as all shipowners were able to comply with the regulation before it started, thanks to the use of biofuels. The “Total cost” column of Table 6 is an aggregation of all costs, and it indicates that S4 is the least expensive scenario for all stakeholders combined.

In S5, the impact of large funding on shore power infrastructures is investigated and reaches USD $1,630 M. In this case, shore power penetrates up to 67 % of the total energy consumed at berth until 2040 and reduces the external costs by 52 %. Alternatively, S6 encompass a realistic budget version of the previous scenario using strategic funding that reached a total of USD $258 M by 2040 for the governments, and a much less restrictive regulation, i.e., the shore power regulation. This funding is realistic as the Canadian Government has already invested similar amounts in the shore power program (Transport Canada, 2012) and the green corridors program (Transport Canada, 2023). The same has been done on a much greater scale in the United States, EU, and China. However, the large downside of S6 is the risk of investing in a network that will not be used if the cost of electricity is too high and the cost of conventional fossil fuel is too low, as shown by the width of the window of possibility.

S7 is used to evaluate the potential of a port incentive on the use of shore power, a system that is currently used in many ports around the world. However, it is not performing much better than the shore power regulation of S6, meaning that there is no strong competitive advantage for shore power with this policy. In S8, regarding the electrical price incentive, the results are much different. The electrical price incentive enables keeping shore power competitive even in cases where fossil fuels are extremely low. As for the case of S2 with the carbon tax, S8 ensures an important emission reduction of 2,033 kt of CO_2e with up to 58 % reduction of external costs. However, the electrical cost incentive means that governments or electrical providers will need to cover a loss of USD ~$2,300 M in electricity funding until 2040. Nevertheless, this electrical funding cost is not equivalent to an investment cost because of the opportunity to increase the electrical demand. Indeed, if there is no shore power, the electrical providers and governments would lose a business opportunity, and shipowners would otherwise use MDO rather than electricity.

Then, S9 investigates the combination of biofuels, zero-emission regulation, strategic funding, and carbon tax. The results indicate an important reduction in external costs of about 70 %. However, the penetration of shore power is mixed, with 55 % of the energy consumed at berth being electricity at the bottom of the window of possibility and only 7 % at the top of the window of possibility. As soon as shore power operational costs are too high, biofuels are preferred instead of shore power because of their low cost.

S10 is very similar to S9 with the exception that the carbon tax is replaced by the shore power regulation. The goal was to see if a shore power regulation could perform better than the carbon tax to ensure that the retrofitted shore power installations are used even if biofuels are considered. The scenario concludes with a lighter uptake of shore power with 52 % for the high shore power penetration case but achieves to ensure a higher minimum usage of shore power when the penetration case of shore power is low, with 27 % of the energy consumed being electricity. For an investment of USD $258 M, S10 can reduce emissions and external costs by 71 % and 64 % respectively. Therefore, S10 can generate more indirect income than it costs to implement in the best case. Also, biofuels still play an important role in this scenario to reduce emissions at berths where it would be too expensive with shore power.

Then, Scenario 11 was intended to see what the maximum possible penetration of shore power could be in the St. Lawrence and Great Lakes for the dry and liquid cargo network. Because the policies cannot be effective from day one, because some ships do not stay long enough at berth or do not visit the St. Lawrence and Great Lakes enough, shore power is limited to a maximal penetration of 81 % of the total consumed energy by 2040, and to reduce the external costs from USD $377 M to USD $73 M.

Further analysis in Appendix C indicates that, across all shore power adoption scenarios, the number of conversions totalized 60–700 for liquid bulk carriers and 200–1,200 for dry bulk carriers, which is similar in share. However, in low-penetration scenarios (S5, S6, S7), liquid bulk carriers are converted first. The domestic fleet of Canadian and U.S.-flagged vessels sees significant shore power uptake (84–110 ships), while the international fleet dominates number of conversions due to their larger numbers. Scenarios combining shore power regulations with strategic funding or port incentives (S6, S7) achieve notable penetration when electricity costs are low and fuel prices are high.

Appendix C also indicates that zero-emission policies are more effective than carbon taxes in driving conversions. Most ships adopt shore power during construction, as retrofitting is much more expensive. Older ships still convert in significant numbers, illustrating that appropriate policies can make shore power economically viable for both new and aging fleets. Finally, liquid carriers are more sensitive to the future cost of electricity and fuels than dry bulk carriers, explaining the large window of possibility in certain cases.

The high-level analysis of the shore power deployment scenarios shows that, with the right policies and regulations, shore power can become less expensive than biofuels 30–50 % of the time. This is considering the most realistic scenario, S10, which includes: biofuels, a shore power regulation, a zero-emission regulation, and strategic funding. The next section investigates the emission abatement cost of the different scenarios.

3.2. Abatement cost curves of emissions

Fig. 4 and Fig. 5 present the abatement cost per ton of emissions reduced through shore power adoption, categorized by berth and ship conversions across all scenarios. An additional analysis of the abatement cost in relation to the number of shore power conversions over the years and through the fleet is provided in Appendix C. The x-axis of Fig. 4 and Fig. 5 represents the abatement cost, and the y-axis represents the berths or the ships. Two curves for each scenario are displayed as they represent the case with a high cost of fuel and low electricity cost, and the case with low fuel cost and high electricity cost. The shaded area between each combination of curves represents the scenario's window of possibility.

Fig. 4 indicates that for most scenarios, a share of the emission reductions can be achieved at a negative abatement cost. Based on the figure, it can be assumed that ~ 20 berths have a very strong shore power potential with excellent economic impact. Most berths can be converted at a cost that is between USD −\$100/tCO_2e and USD \$115/tCO_2e. S1 has no berths converted to shore power and doesn't appear on the graph. S2 and S3, which include the carbon tax, both achieve emission reductions at negative cost, but only a small total number of berths are converted. S4 achieved the same result with a maximum of ~ 15 berths converted. S9 and S10 also achieve negative emissions for the first few berths. All scenarios with strategic funding achieve a maximal cost of USD ~\$115/tCO_2e, which is in line with most other marginal abatement costs (McKinsey and Compagny, 2013). For scenarios with a full funding policy, the conversion of the very remote berths with only a small amount of emission reduction reaches a very high cost (represented by ∞ in the figure) since these berths can have very close to zero tons of CO_2e. Therefore, not all berths must be electrified because the funds would not be spent wisely.

In Fig. 5, the same analysis is performed for ships.

In general, most converted ships, regardless of the scenario, achieve a conversion cost between USD −\$1,000/tCO2e and USD \$500/tCO2e. However, all scenarios finish at very high abatement costs because the last ships to be converted to shore power have a small utilization compared to the high cost of conversion to shore power. While typical maritime decarbonization technologies should be at or below \$240/tCO_2e (Longva et al., 2024) by 2040, this study does not account for a global shore power uptake worldwide. Such a global deployment would have the effect of improving the high abatement costs of international ships that only spend a limited time in the St. Lawrence and Great Lakes shipping network.

S5 and S11 benefit from the full funding, and the cost of reducing the emissions goes up quickly to reach about USD \$7,500/tCO_2e for the ships that do not spend a lot of time at berth. The case of the S5 shows that only a small number of ships, between 100 and 400, need to be converted to achieve important emission reductions, as presented in Fig. 3. However, converting systematically all the ships with the most emissions is not necessarily strategic since it comes with a very high cost of emission reduction. S2 presents a case where

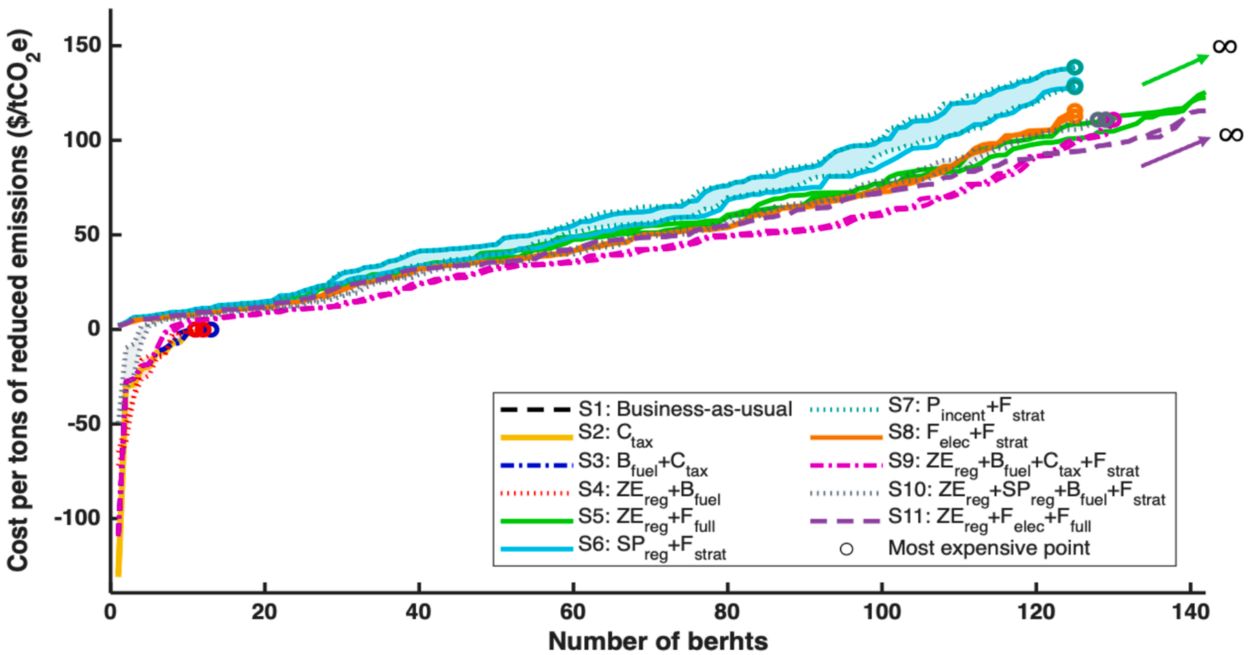

Fig. 4. Abatement cost per ton of reduced emissions per berth for each scenario in USD.

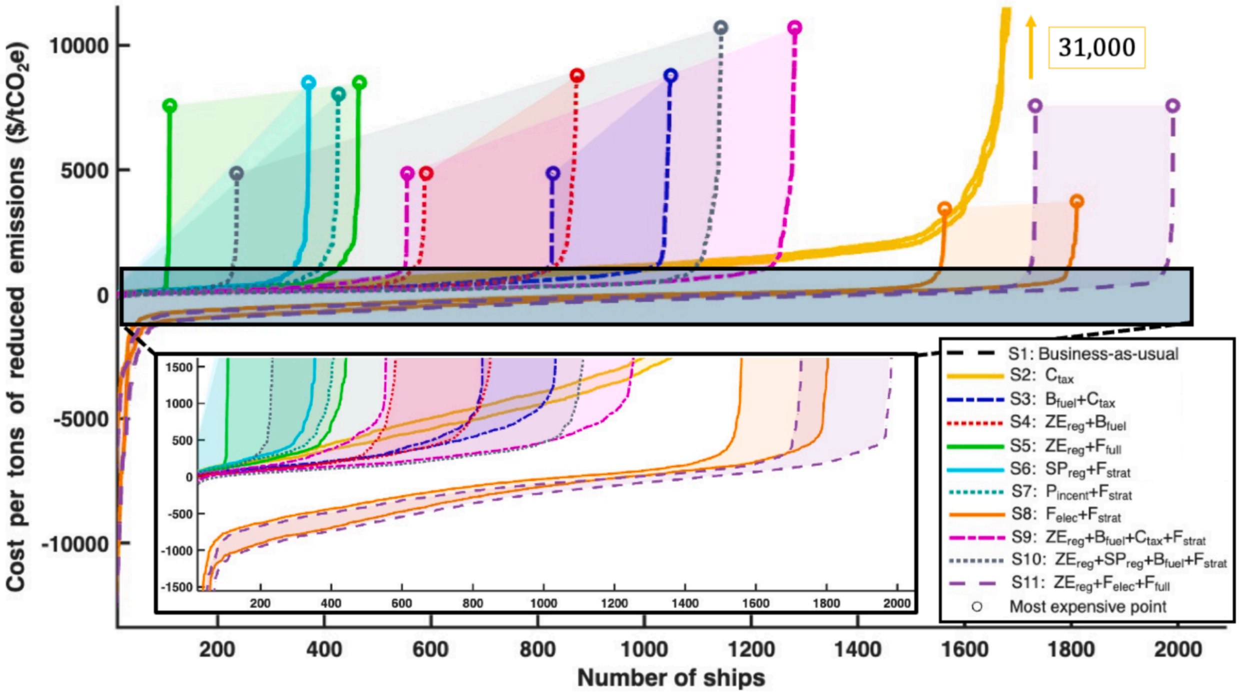

Fig. 5. Abatement cost per ton of reduced emissions per ship for each scenario in USD.

the abatement cost increases linearly until the last ship, and where the abatement cost reaches an extremum. S9 and S10 have the largest window of possibility, with a difference of ~ 800 ships that are converted to shore power. Also, even if S8 uses strategic investment funding, which is much smaller than the full funding of S11, S8 achieve a similar number of ship shore power conversions. It shows that full funding is not essential to achieve good results. Finally, excluding S1, S6 and S7 have the fuel and electricity cost combination that results in the smallest number of converted ships, with only 6 ships converted to shore power in the worst case.

Another key finding is that, despite the full funding policy in S5, international ships are excluded as funding is restricted to domestic vessels and berths. Therefore, only a limited number of ships proceed to the shore power conversion and prefer to pay for the shore power penalties.

Additionally, converting a vessel to shore power does not necessarily require a scheduled dry-dock, and can be done at any long stay in port. The work involves installing and testing a transformer, shore power connection panels, sockets, and an onboard receiving switchboard. Most ships sailing through the St. Lawrence and Great Lakes are optimized for the lock system, and the space availability for the transformer is limited, which can have an impact on costs and retrofit time. However, these challenges should not affect the model as a lot of time is allowed for the ships and ports to prepare.

Finally, Appendix C data reveal that most shore-power conversions for international ships occurred when the ships were being built. Based on the literature review findings, integrating equipment during construction simplifies the installation and cuts CAPEX by up to 50 % compared to retrofits. Then, the vessel age at which the shore power conversion occurs declines sharply but rebounds at around 12–15 years, coinciding with the ~ 12–13 year average age of the global bulk carriers and tankers fleet. Therefore, the model shows that shore power investment can still be considered for mid-life ships thanks to shore power policies. Finally, the conversions on vessels older than 25 years are predominantly done on domestic vessels.

4. Conclusion

The study presented a framework that can be used by policymakers to evaluate shore power policy pathways including the impact of alternative fuels. The analysis offers insights into shore power economic viability and environmental benefits until 2040 under different scenarios for the dry and liquid bulk shipping network of the St. Lawrence and Great Lakes.

The key findings indicate that various roadmaps could enable the penetration of shore power in the St. Lawrence and Great Lakes, highlighting the critical importance of selecting the right policy framework to reduce emissions and to ensure fair cost-sharing among stakeholders. However, under the "business-as-usual" scenario, shore power is unlikely to penetrate the shipping network. The emissions of the studied shipping network would reach 3,406 kt of CO_2e by 2040, generating USD $377 M in external costs related to air pollution and environmental disasters.

Depending on the scenario, external costs and emissions can be reduced by up to 90 % with shore power and biofuels. However, certain regulations impose significant costs on stakeholders. For instance, carbon taxes burden shipowners, whereas full funding subsidies place heavy financial strain on governments. Also, the less expensive regulations are the zero-emission and shore power regulations.

Under the appropriate policy framework, shore power can be more cost-effective than biofuels in 30–50 % of vessels' total operational energy demand at berth. This is based on the most realistic policy scenario including: shore power regulation, zero-emission regulation, biofuels, and strategic funding. For an investment of USD $258 M, this policy combination can reduce emissions by 2,556 kt of CO_2e and external costs on society by USD $240 M by 2040. Additionally, this scenario can cost less to implement than the indirect income it will generate for society. Notably, biofuels play a crucial role in this scenario by reducing emissions at berths where implementing shore power would be too costly.

In contrast, policies limited to a zero-emission-at-berth regulation would favour biofuels, as the model assumes that biofuel costs are equal to marine diesel and does not account for the costs of biofuel storage and bunkering infrastructure. If biofuels or alternative fuels price stays very low (USD ~$600/t), shore power will not be able to compete with them without subsidies. Nonetheless, shore power has more chances of becoming more affordable for an important number of vessel port calls because the biofuel average cost in 2022 in the Great Lakes was about USD $1,527/t. This number is higher than the maximum fuel cost (USD $1,000/t) that was tested in the model and would result in an electrical cost of USD $0.28/kWh, which is typically higher than electricity from shore.

In addition to policy choices, various factors impact the feasibility and cost-effectiveness of shore power deployment. Notably, once a certain number of shore power conversions are done, the shore power deployment benefits from an effect of scale, which reduces overall costs. Also, keeping electricity costs low is essential to promoting shore power, regardless of fuel price variations. Scenarios with strategic funding consistently achieve significant cost-effectiveness, with shore power abatement costs between USD −$100/tCO2e to USD $115/tCO2e aligning with common marginal abatement costs in other sectors. Notably, around 20 berths exhibit high potential for shore power adoption. However, not all berths require electrification to optimize funding allocation because many underutilized berths involve a poor cost-benefit ratio. The ships on their end have a much larger range of emission abatement costs between USD −$1,000/tCO2e to USD $500/tCO2e. Shore power readiness is most often addressed at the newbuilding stage, since retrofitting existing vessels is more expensive. Nevertheless, policies play a decisive role in supporting retrofits of older ships, particularly when favourable funding structures and incentives are available.

In summary, the primary contribution of this study is the development of an evaluation framework to identify the most effective set of shore power deployment policies and strategies. The model employs game theory and scenario analysis to address multiple combinations of policies and regulations in relation to various alternative fuel scenarios. In total, eleven scenarios were studied, each with different policy combinations: zero-emission at berth regulation, carbon tax, shore power regulation, alternative fuels, strategic funding policy, full funding policy, electrical cost incentive subsidy, and port incentive.

4.1. Policy recommendations

On the basis of the dry and liquid cargo test case of the St. Lawrence and Great Lakes included in this study, policy recommendations can be formulated. The test case recommends a policy framework combining strategic funding for shore power, increased marine biofuel adoption, prioritization of shore power conversions at high-impact berths and ships, a zero-emission regulation at berth, and mandatory shore power connections for ships at berths with shore power capabilities in the St. Lawrence and Great Lakes. These policies enable a balance between emission reductions and cost-sharing while providing the scale economies needed for long-term viability.

The shore power policy mandating shore power connections for shore power capable ships at berths with shore power capabilities is a fundamental element of successful deployment. It guarantees a minimum level of utilization, thereby supporting the recovery of infrastructure investments. Without such a policy, shore power projects face a high risk of becoming stranded assets.

Then, strategic funding, shore power regulations, and zero-emission requirements at berth are practical, cost-effective, and feasible policies, as demonstrated by their successful implementation in California, the EU, and China. Biofuel is also the alternative fuel that is the most practical to use in the St. Lawrence and Great Lakes, as it is already in use by many ships. Therefore, it is estimated that biofuels will play a role in conjunction with shore power.

Zero-emission-at-berth policies should allow shipowners and ports flexibility to choose preferred technologies or measures while explicitly covering all at-berth emission sources. To realize the full benefits of shore power, policies must encompass onboard sources such as auxiliary engines and boilers. Otherwise, greenhouse gas and air pollutant emissions will persist and diminish the environmental and economic effectiveness of both ship and shore investments. Partial regulation risks leaving important emission sources unaddressed and creating counterproductive incentives that reduce overall cost-effectiveness.

Other policy options present challenges. Carbon tax could significantly reduce emissions but would likely increase freight transportation costs, which may ultimately be passed on to consumers. Full funding subsidies would be prohibitively expensive and inefficient in resource allocation. Port incentives can significantly influence shore power adoption but are typically implemented at the discretion of individual ports. Finally, an electrical cost subsidy has important implications: while it stimulates electricity demand, which benefits providers on the long term, it does so at a subsidized rate that reduces their overall income.

Based on the St. Lawrence and Great Lakes dry and liquid shipping network test case, policymakers can see how to use the framework for any given shipping network.

4.2. Future work

Future research should prioritize optimizing the design and investment strategies for electrical substations and integrating them into the model to enhance the overall efficiency of shore power deployment. Additionally, incorporating specialized optimization algorithms into the funding allocation process could help prioritize berths and ships with the highest emission reduction potential. Integrating dynamic budget constraints into the model would enable more realistic and adaptive funding strategies over multi-year periods.

Finally, the regional economic impacts of shore power merit more detailed study. Most onshore capital and operational expenditures are spent locally and therefore have the potential to stimulate employment, tax revenues, local businesses, etc. However, these benefits remain largely unknown. Robust regional economic analysis would help demonstrate the macroeconomic case for shore power projects.

CRediT authorship contribution statement

Hugo Daniel: Writing – original draft, Software, Methodology, Investigation. **João Pedro F. Trovão:** Conceptualization, Funding acquisition, Resources, Supervision, Validation, Writing – review & editing. **Loïc Boulon:** Writing – review & editing, Validation, Supervision, Resources, Funding acquisition, Conceptualization. **David Williams:** Writing – review & editing, Resources, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Joao Pedro F. Trovao reports financial support was provided by Canada Research Chair Program (950–230672). Joao Pedro F. Trovao reports financial support was provided by Mitacs Accelerate Program (IT17570 and ITIT32307). David William reports financial support was provided by FEDNAV INC. Joao Pedro F. Trovao reports administrative support and travel were provided by Portuguese Foundation for Science and Technology. Joao Pedro F. Trovao reports administrative support was provided by Portuguese Recovery and Resilience Plan. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Symbol	Definition
Variables	
C_{bPen}	Berth penalty cost
C_{conn}	Cost of connecting and disconnecting the ship
C_{elec}	Electricity cost
C_{ext}	Environmental and social costs related to a berth
C_{fuel}	Fuel cost
$C_{NewBuilding}$	Investment cost of a new ship
$C_{OP\ AE}$	Operational cost
C_{OPtot}	Yearly total operational costs
C_{pens}	Ship's penalty cost
$C_{Retrofit}$	Investment cost of a shore power conversion or retrofit.
C_{RH}	Cost per hour of running the auxiliary engines
C_{tax}	Carbon tax
EC	Electrical consumption
E_{CO2e}	Carbon dioxide equivalent emissions
FC	Fuel consumption
I_{SP}	Annualized investment in shore power
i_r	Interest rate
Pen	Ship's penalty cost per hour
$P_{OP\ SP}$	Potential income from shore power for the port
$P_{OP\ SP}$	Potential cost of shore power
$P_{bOP\ SPtot}$	Total potential operational shore power costs for berths
$P_{sOP\ SPtot}$	Total potential operational shore power costs for ships
R_{blend}	Blend ratio of a fuel
Subscript	
Bio	Biofuels
f	Fuel type
F	Subset of all fuel types

(*continued on next page*)

(*continued*)

Symbol	Definition
H	High penetration case of shore power
L	Low penetration case of shore power
st	Ship type
ST	Matrix of port calls
TIP	Time in port
Y	Year
Y	Lifespan of ships
Abbreviations	
AE	Auxiliary engines
B_{fuel}	Biofuel
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
C_{tax}	Carbon tax
E_{incent}	Electrical price incentive
F_{full}	Full funding policy
F_{strat}	Strategic funding policy
GA	Genetic algorithm
GHG	Greenhouse gas
MDO	Marine diesel oil
NO_x	Nitric oxides
P_{incent}	Port incentive
PM	Particulate matter
SO_x	Sulphur oxides
S1	Scenario 1
S2	Scenario 2
S3	Scenario 3
S4	Scenario 4
S5	Scenario 5
S6	Scenario 6
S7	Scenario 7
S8	Scenario 8
S9	Scenario 9
S10	Scenario 10
S11	Scenario 11
SPDP	Shore power deployment problem
SP_{reg}	Shore power regulation
ZE_{reg}	Zero-emission regulation

Appendix B

Detailed model flowchart

Fig. 6 presents the detailed flowchart of the model.

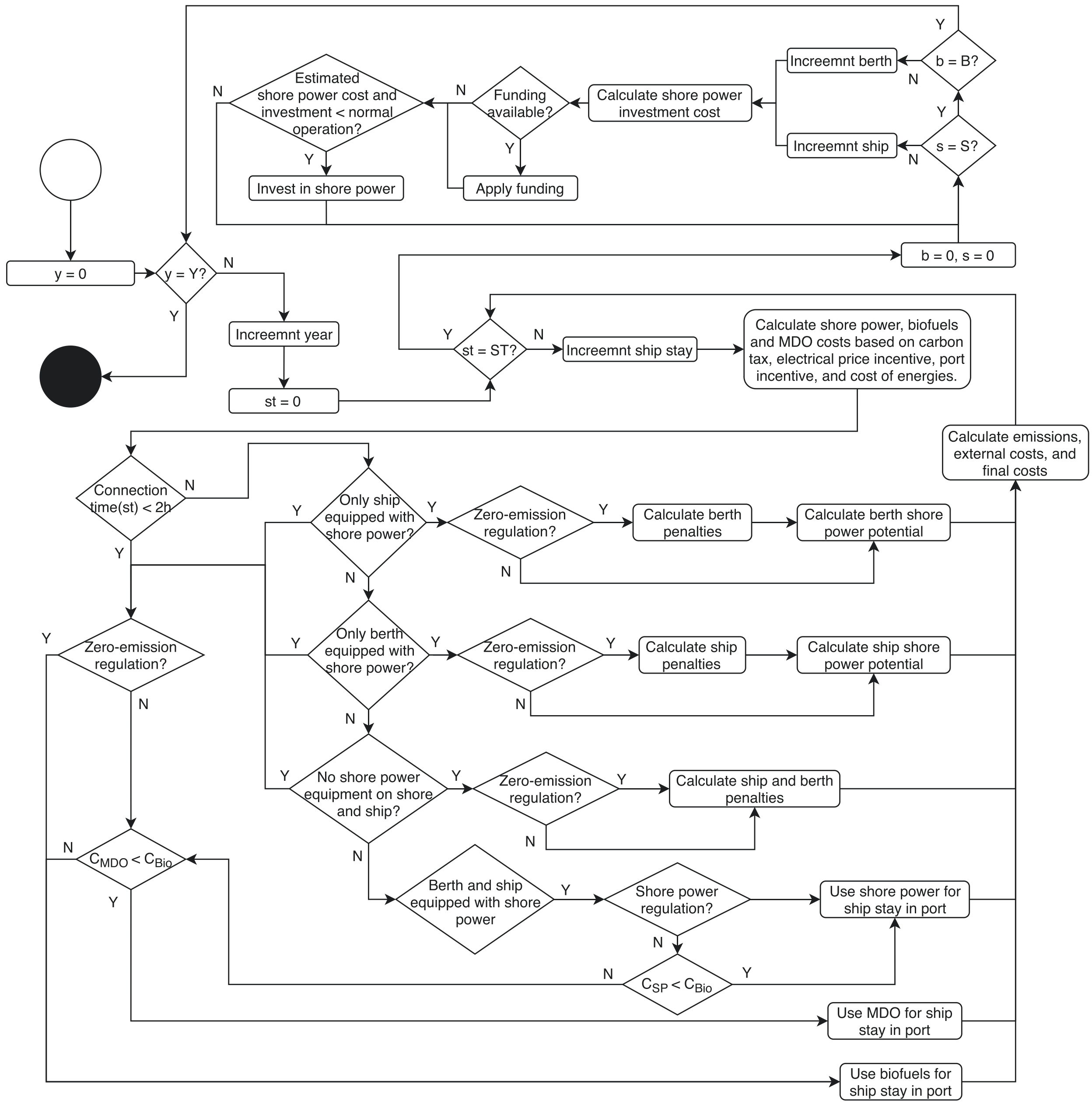

Fig. 6. Flowchart of the suggested model

Scenario and policy description

Scenario 1: Business-as-usual

In this scenario, there are no environmental policies applied by governments, ports or shipowners, and the market decides which energy is consumed. To simulate the growth of the business-as-usual emissions over the years, a linear growth factor of 1 % is applied to the annual emissions. The factor is based on the Great Lakes and St. Lawrence Seaway System traffic growth from 1995 till now (SLSTL

Seaway, 2025).

Scenario 2: Carbon tax policy

The carbon tax and its impact on the shipping network are investigated in Scenario 2. The carbon tax consists of an additional cost per ton of carbon dioxide equivalent emissions E_{CO2e} that is emitted by ships. This scenario is used to simulate IMO's midterm measures to decarbonize the industry and the EU ETS. A small carbon tax in the order of hundreds of dollars per ton of CO_2e will only be a cost passed on to the consumers and will not have a major impact on the industry. However, a large carbon tax in the order of thousands of dollars per ton of CO_2e is expected to have a real impact. Therefore, a carbon tax C_{tax} of USD $1,000/t of CO_2e is investigated in this scenario, and its total cost per ship stay in port C_{Ctax} can be estimated as per equation (B.1):

$$C_{C_{tax}(st)} = E_{CO_2e} \times C_{tax} \tag{B.1}$$

Eq. (B.1) is added to (1) to include the carbon tax in the operation cost of using MDO.

While small carbon tax prices are not directly investigated, they can still be encompassed in high fuel costs. If the modelled fuel cost is USD $600/t, it can be assumed that any carbon tax from zero to USD $400/t should produce an outcome that will lie in the scenario window.

To allow the industry time to prepare for the carbon tax, a delay of two years is given before the carbon tax policy takes effect.

Scenario 3: Biofuels and carbon tax policies

In this scenario, the combination of a biofuel policy and a carbon tax is investigated. The biofuels policy, denoted *Bio*, has the potential to reduce an important share of the carbon emissions of shipping in the St. Lawrence and Great Lakes, as highlighted in many Canadian studies (Oberhart, 2024), (Rioux et al., 2023), and (Rutherford et al., 2024). Biofuels are used on a few ships right now in the Great Lakes and St. Lawrence. However, the bunkering infrastructure is not deployed on a large scale. To achieve a wide deployment of biofuels, the private sector needs policies and measures from the government which will settle the market and lower their risk (Angelucci et al., 2022).

As governmental measures promoting biofuels will first cover biofuel production and distribution on a national level and for every transportation mode, the governmental cost of promoting biofuels specifically for the maritime industry is not considered in this work. On the ship side, it is considered that the ships use biofuels directly in their auxiliary engines without investment.

Finally, the biofuels storage and bunkering infrastructure need to be deployed, which takes time. To include this progressive adoption of biofuels in the St. Lawrence and Great Lakes and to account for the deployment time of the additional production infrastructure in Canada and in the United States, a fuel blend with MDO is used and detailed in eq. (B.2), and eq. (B.3):

$$FC_{Bio(st)} = R_{blend(y)} \times FC_{(st)} \tag{B.2}$$

$$FC_{MDO(st)} = (1 - R_{blend(y)}) \times FC_{(st)} \tag{B.3}$$

In eq. (B.2), and eq. (B.3), the biofuel blend ratio R_{blend} is a function of the year y. A progressive linear deployment is implemented over three years. These equations are aggregated in eq. (1) to modify the operational cost based on the fuel content.

Scenario 4: Zero-emissions regulation policy and biofuels

In this scenario, a zero-emission regulation is used to prevent the emissions of GHGs at berth. A good example of such a policy is the At Berth regulation of CARB (CARB, 2020a) which does not necessarily force ships to use shore power, but any technology or alternative that will achieve the same result of having no air pollutant emissions at berth. In the case of this work, the ship has the option of using biofuels or shore power to comply with the regulation. However, if it is not economical for the ship to comply, it can also pay the penalties as per eq. (B.4).

$$C_{sPen_{s(st)}} = TIP_{(st)} \times Pen_s \tag{B.4}$$

The ship's penalty cost C_{pens} depends on the time spent in port and the ship's penalty cost per hour Pen_s. The penalty cost is based on the CARB penalty (CARB, 2020b). To be integrated into the mathematical problem, eq. (B.4) is added to eq. (1).

Nevertheless, this scenario does not include shore power funding. To give industry time to prepare for the policy, a period of five years is provided before the policy is enforced. After this period, the ship will be penalized if it does not comply.

Scenario 5: Zero-emission regulation and full funding policy

Scenario 5 investigates the combination of a zero-emission regulation along with the availability of a full funding program for berths converting to shore power and domestic ships reaching 100 % of the investment for all shore projects that apply to the funding program. Also, the funding program is available for 5 years. After the first five years, the funding stops, and the regulation is enforced.

Scenario 6: Shore power regulation and strategic funding policy

In this scenario, the only regulation that is enforced by governments is a shore power regulation. The regulation aims to ensure that shore power capable ships visiting shore power capable berths are also forced to connect. This type of regulation has many benefits:

- Promotes the use of shore power

- Reduces the risk of investing in shore power for ports as they benefit from a secure demand
- Protects the shore power investments of governments
- Stabilizes the electrical energy demand for electrical providers, which enables them to better plan their electrical distribution network, and also increases electrical demand.

The shore power regulation has a penalty that is applied to ships and berths that do not comply with the policy based on the Fig. 2 energy use map. The ship penalty function of eq. (B.4) is applied to the ship if it does not comply, but the berth penalty C_{bPen} is charged with a different penalty function that is proportional to the environmental and social costs C_{ext} that it should have prevented as per (B.5):

$$C_{bPen_{s(st)}} = Cext_{(st)} \tag{B.5}$$

In addition, a strategic funding program is available. The strategic funding program consists of providing 100 % funding for shore power projects that are targeted by the government as the ones having the highest emission reduction potential. As highlighted in (Daniel et al., 2024), the shore power potential in the Great Lakes and St. Lawrence could reduce USD $25 M per year in external costs, premature deaths, and environmental costs. Therefore, a yearly strategic funding of USD $25 M is available for the program with USD $25 M for the berths and USD $5 M for domestic ships. In the end, the total funding will diminish with the years as more and more berths and ships are converted to shore power.

This type of policy combination has a lot of potential for its applicability and low cost. First, it enables investment in shore power where it makes the most sense. Second, it protects the investment by ensuring the utilization of the system by the ship that installed shore power. Finally, it is not a strong binding regulation since all shore power installations and usage are made because it is economic.

Scenario 7: Port incentive policy

The port incentive policy is about simulating the voluntary incentives of ports toward shore power. To do so, ships using shore power will benefit from a reduction in their docking fees, which makes it more interesting for them to connect. However, the port incentive is financed by the port itself, which reduces its income from shore power and therefore reduces the shore power adoption among ports. As per the “Green Vessels” financial incentive programs in Canadian ports (Ushio, 2023), the port incentive is set to USD $1,000 for each stay in port of a ship using shore power. To apply the port incentive to the model, eq. (9) is modified as follows in eq. (B.6):

$$C_{sOPSP(st)} = EC_{st} \times C_{elec} + C_{conn} - P_{inc} \tag{B.6}$$

Scenario 8: Electrical price incentive policy

The electrical price incentive is a market measure targeting the operational cost of using shore power. By making electricity less expensive, it enables shipowners to benefit from more funds to invest in shore power. In this case, a subsidy of USD $0.05/kWh is applied. To apply the port incentive to the model, eq. (9) is modified as follows in eq. (B.7):

$$C_{sOPSP(st)} = EC_{st} \times (C_{elec} - C_{inc}) + C_{conn} \tag{B.7}$$

Scenario 9: Zero-emission regulation, biofuels, carbon tax, and strategic funding policies

Scenario 9 is a combination of the zero-emission regulation, the use of biofuels at berth, the implementation of a carbon tax, and a strategic funding policy. This specific mix of policies is selected because it is a likely possible future. Zero-emission and shore power regulations have been implemented in the EU, California and China, making it more than likely for Canada to adopt the same type of regulation. Then, biofuel, as described in (Oberhart, 2024) is the main alternative fuel considered in the St. Lawrence and Great Lakes. The carbon tax might be adopted by the IMO and is already in place in Europe. Finally, a strategic funding policy is more realistic than a full funding strategy, as the total budget is limited.

Scenario 10: Zero-emission and shore power regulations, biofuels, and strategic funding policies

Scenario 10 is also a multiple policy combination including zero-emission and shore power regulations, the use of biofuels, and strategic funding. Differently from Scenario 9, there is no carbon tax, and each shore power capable ship calling at shore power capable berths is required to connect. This is making shore power more economical because the system usage is optimized.

Scenario 11: Zero-emissions regulation, electrical incentive, and full funding policies

The last scenario combines the zero-emission policy with electrical price incentives and full funding. This scenario will most likely be the most expensive since biofuels are not included to offer economic alternatives to shore power, because the cost of shore power operation is small, and because every shore power project is funded. However, the scenario is relevant to see how much emission could be eliminated by shore power at maximum. Indeed, some emissions cannot be eliminated by shore power because the ships are not at berth long enough, because costs are impossible to recover or simply because installations take time to get built.

Appendix C

Extended analysis of the abatement cost of emissions

Fig. 7 and Fig. 8 present the average cost per ton of reduced emissions for berths and ships respectively, and per year for each scenario. The x-axis is the years, and the y-axis is the average cost. The shaded area between the two curves of the same scenario is the window of possibility. The goal is to see how the cost of converting berths and ships to shore power evolves over the years.

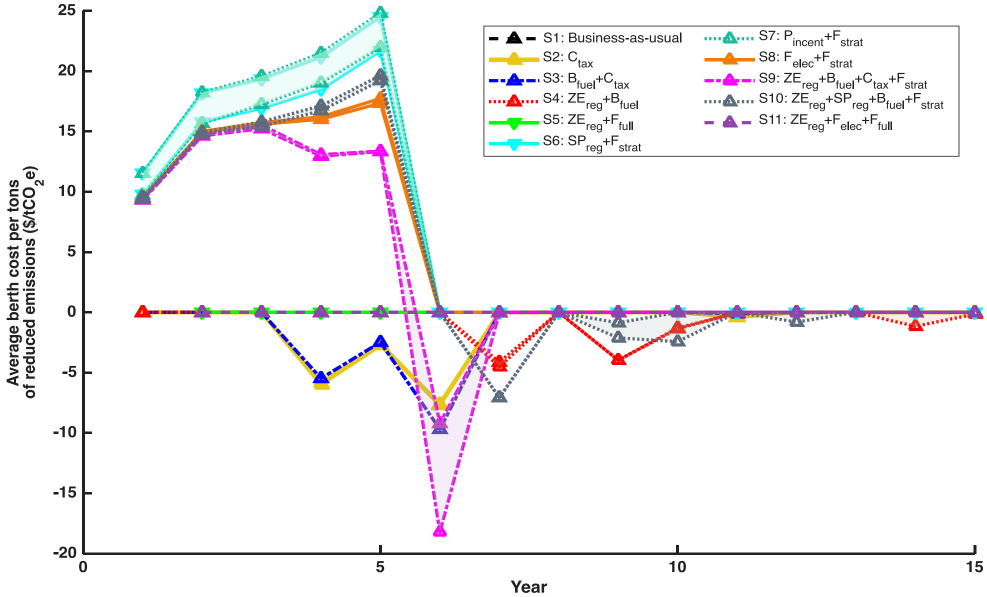

Fig. 7. Average cost per ton of reduced emissions for berths per year for each scenario

Fig. 7 shows that the berth cost increases until the fifth year, when the funding program finishes. However, in the case of S6, S7, and S10, the cost becomes negative thanks to an effect of scale since enough berths are converted in the network. It enables new converted berths to be visited by enough converted ships and results in a more economic deployment of shore power. As per Fig. 4, S5 and S11 have no cost since the entire berth conversion cost is funded. Finally, scenarios 2–3-4–9-10 all achieve a negative average cost thanks to funding or other policies.

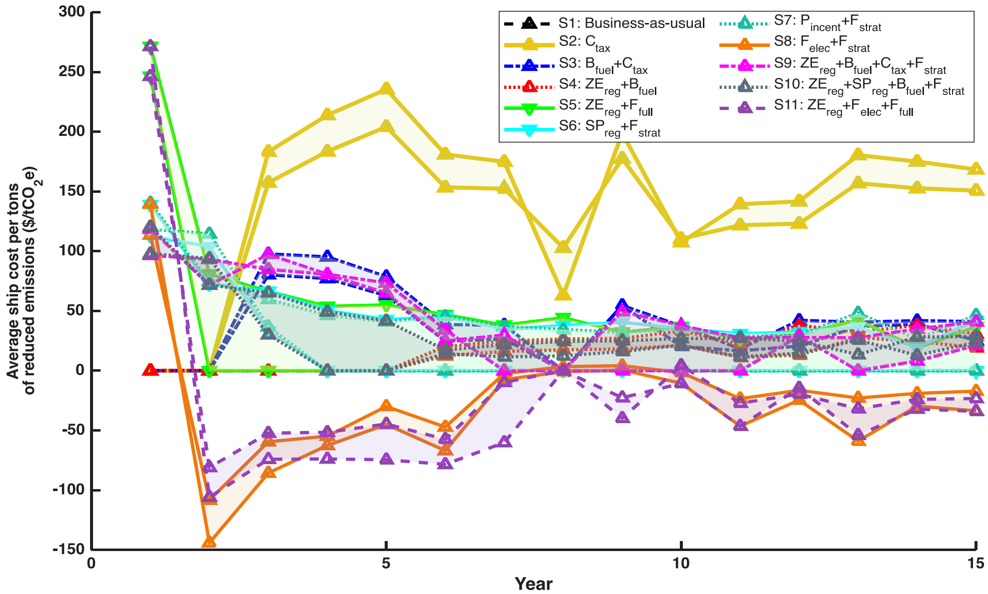

Fig. 8. Average cost per ton of reduced emissions for ships per year for each scenario

In the case of the ships in Fig. 8, the average cost of converting ships to shore power varies in different ways, but all scenarios tend to converge toward zero over the years. S8 and S11 are the only ones that achieve a negative yearly average cost of emission reduction. This shows that a low electricity cost greatly impacts the economics of shore power for the ships. S5, S6, S7, and S9 can see a slowly decreasing cost over the years, thanks to the effect of scale. When more berths are converted to shore power, it becomes more and more economical for ships to convert. S2 shows that no matter the cost of electricity or the cost of fuel, the window of possibility for a carbon tax policy is very small, and the cost of shore power conversion for ships is not very much affected.

Analysis of the shore power network deployment in time and across the fleet

Fig. 9 and Fig. 10 present the number of converted berths and ships respectively that are converted to shore power each year, and for each scenario. The x-axis is the years, and the y-axis is the number of ship conversions. The shaded area between the two curves of each scenario represents the window of possibility.

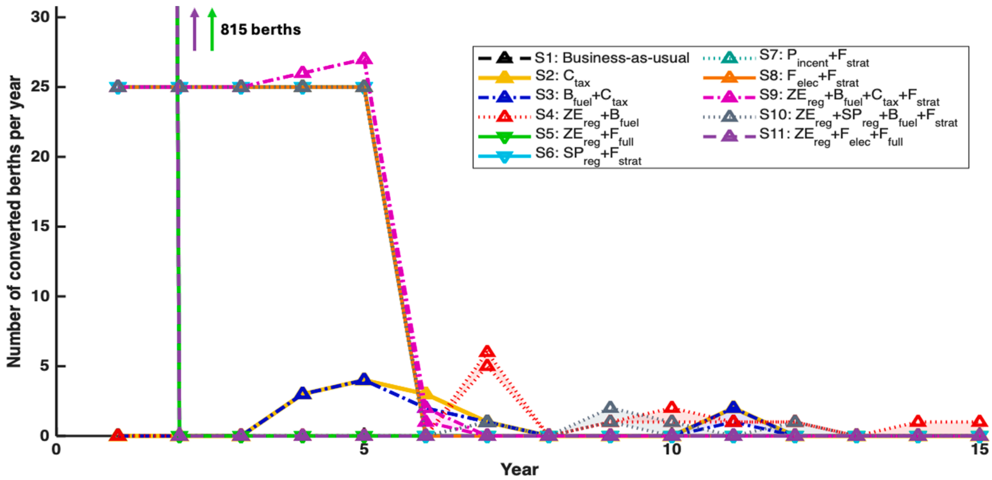

Fig. 9. Annual number of berths converted to shore power for each scenario

Fig. 9 shows that the number of converted berths reaches 815, i.e., all the berths of the network in the first year for S5 and S11 since they have access to a full funding policy. Then, the scenarios that have a strategic funding policy convert 25–27 berths per year, which is more realistic. Finally, S2, S3, and S4 have a carbon tax and no other policy. They see a slow increase in the number of converted berths after a few years.

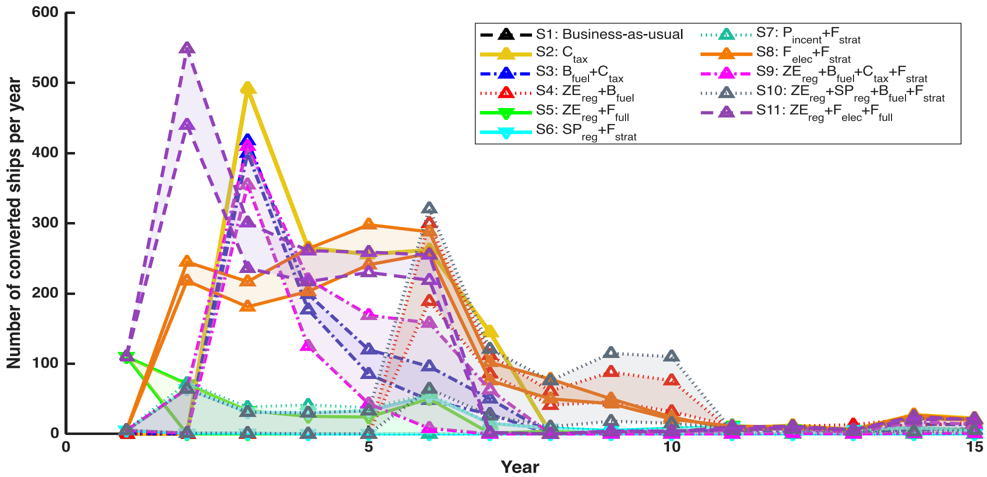

Fig. 10. Annual number of ships converted to shore power for each scenario

In the case of the ship conversion, scenarios S2, S8, S9, and S11 see a very fast increase in the first years at a pace of ∼ 400 per year. Scenarios S3, S4, and S10 show the same result, but after the 6th year when the zero-emission regulation enters into force. For S3, it is harder to understand. Most likely, it is explained by a waterfall effect on the network, where other conversions have made the business case for shore power possible. After the 10th year, the number of new conversions flattens drastically as the economic conversions are already done.

Fig. 11 presents the shore power penetration in the different ship types and fleets, i.e., liquid bulk carriers, dry bulk carriers, domestic ships, and international ships. The black bar represents the total number of converted ships for reference purposes. Therefore, the liquid and dry bulk ships can be compared as their summation equals the total number of ships. The same can be done with the domestic and international ships. To represent the window of possibility between the low shore power penetration case (L) and the high penetration case (H), two bars of a similar colour are represented per ship type and fleet type. The x-axis represents each scenario, and the y-axis represents the number of converted ships.

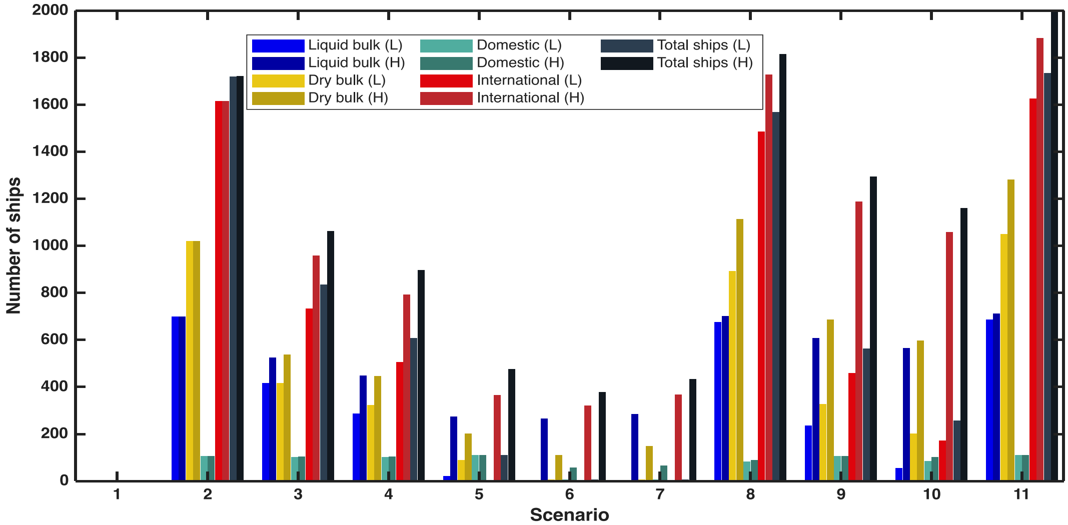

Fig. 11. Total number of ship conversions to shore power per scenario for liquid bulk carriers, dry bulk carriers, domestic ships, international ships, and the total number of ship conversions.

In all scenarios where shore power has some relevant penetration, the liquid bulk carriers and the dry bulk carriers follow a similar total share of conversions with ∼ 60–700 liquid bulk carriers, and ∼ 200–1,300 dry bulk carriers. The difference between domestic and international vessel conversions is expected, given the fleet composition. The region hosts only 21 domestic liquid carriers and 89 domestic dry bulk carriers, compared to 761 international liquid carriers and 2,245 international dry bulk carriers. In low-adoption scenarios such as S5, S6, and S7, liquid bulk carriers are more frequently converted, likely due to their longer port stays.

Policy design also contributes to this disparity. In the model, funding is limited to domestic vessels, excluding most international ships. IMO rules and the new mid-term measures aim to cut GHGs but do not mandate shore power, while still indirectly encouraging it. Since 2025, EU policies like FuelEU Maritime and the EU ETS penalize emissions, pushing international ships toward shore power, especially cruise and container vessels (shore power mandate in 2030). However, these rules do not apply to the domestic ships of the St. Lawrence and Great Lakes.

Then, scenarios 2–3–4–5–8–9-10–11 all have between 86 and 110 ships from the domestic fleet that are converted to shore power, which represents most of the domestic fleet. Therefore, shore power has a great penetration over Canadian and United States flagged ships. For the internationals, they make most of the ship conversion since they are in much greater numbers.

S6 and S7, which include the shore power regulation combined with the strategic funding and the port incentive combined to the strategic funding respectively, are the scenarios where a low cost of electricity and a high cost of fuel are required to reach some level of shore power penetration.

S3 and S4, which both consider biofuels but with carbon tax policy in the first scenario and zero-emission regulation in the second, are equal in terms of ship and berth shore power conversions as presented in the previous figures. However, Table 6 shows that the S4 is much less expensive for the shipowners. Therefore, for similar results, the zero-emission policy should be prioritized over the carbon tax policy.

Fig. 12 presents the age in years of the ships when they converted to shore power with the number of ships for the high penetration scenario of shore power, and for each ship's age. The x-axis is the age of the ship when it converted to shore power with zero being a new building, and the y-axis is the number of ships that converted at this age. Fig. 12 a) presents the domestic ships, while Fig. 12 b) presents the international ships.

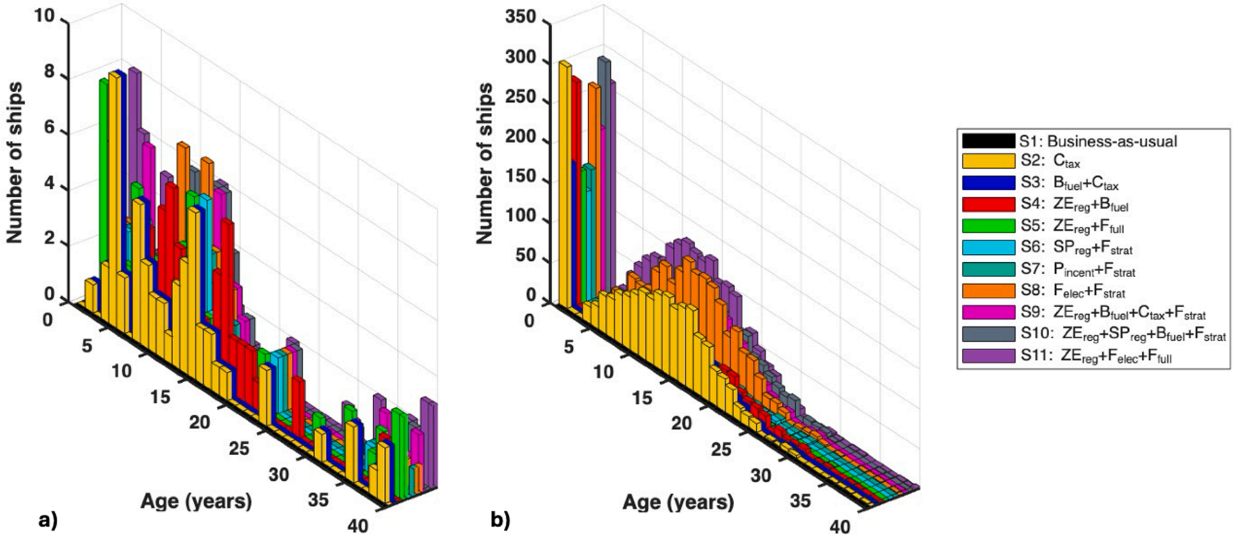

Fig. 12. Number of ships in function of their age when they converted to shore power for a) the domestics, and b) the internationals

The age of ships when they converted to shore power highlights two important findings. First, most ships that convert to shore power do it when they are built, i.e., at year zero. As a ship is being built in the shipyard, it is much easier to install the shore power equipment resulting in lower costs. Then, the number of ships that perform a retrofit drastically falls close to zero and augments slowly until about 15 years old. This last result can be explained by the age of the world fleet of bulk carriers and tankers, which is ~ 12–13 years. However, the large number of old ships that convert to shore power is also considerable in most scenarios, showing that the policies make the business case of shore power possible even for older ships. Finally, the ships that are converted after 25 years old are mostly domestic ships that only sail in the St. Lawrence and Great Lakes.

High-level analysis of the shore power deployment segregated by ship types

Complementing Section 3.1, the high-level analysis on the shore power deployment and external costs reductions has been segregated by ship types: dry bulk carriers in Fig. 13 and liquid carriers in Fig. 14. The objective is to provide more details on both networks individually, even if they share multiple berths.

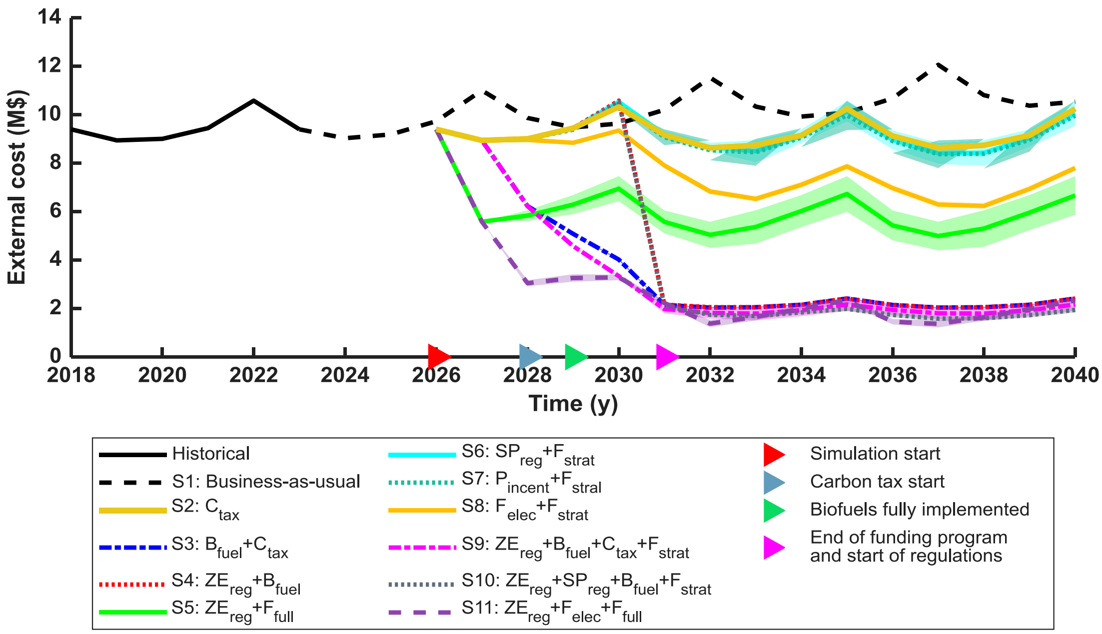

Fig. 13. Scenario analysis for dry bulk carriers: Annual external costs

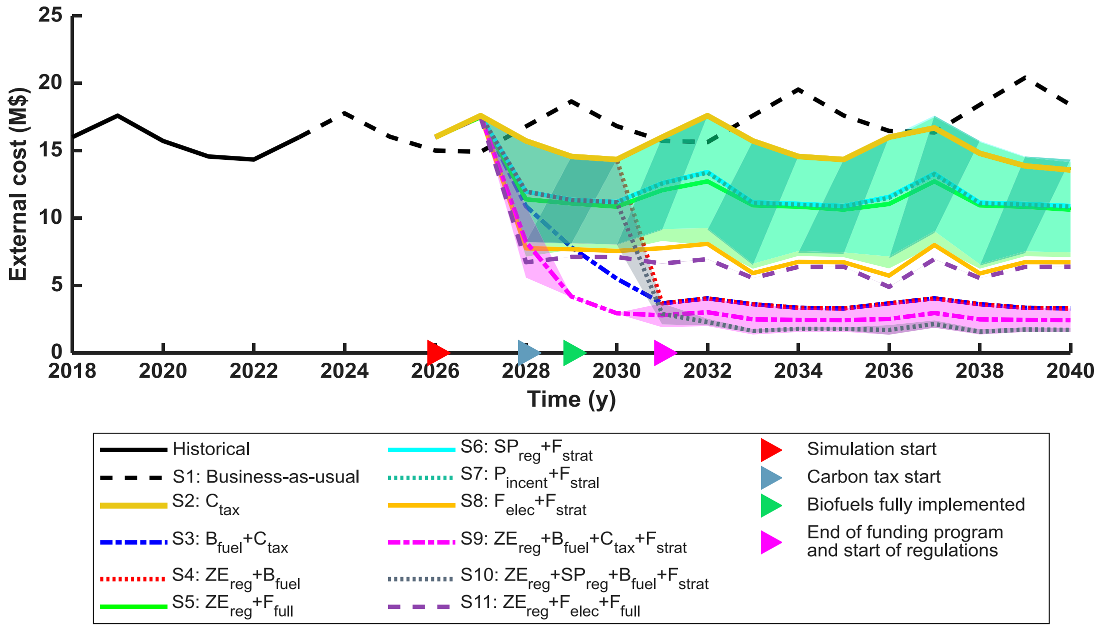

Fig. 14. Scenario analysis for liquid carriers: Annual external costs

The results show that in both cases, the S10 is the most realistic scenario that can reduce external costs the most. Also, the liquid carriers are the ones that are the most affected by the future cost of electricity and fuel for the adoption of shore power, resulting in a large window of possibility. On the other hand, dry bulk carriers are less affected by future operational cost disturbances.

Data availability

Data will be made available on request.

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