Currents of Change: Social-Environmental Valuation of Electric Ships for Sustainable Passenger Transport

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Abstract

Air and maritime transport services enable mobility and economic and social development, but they have significant environmental impacts. To reduce carbon emissions, there is a growing trend towards adopting electric ships for short-distance passenger transport. Nonetheless, there is a lack of appropriate valuation frameworks. This paper proposes a framework specifically tailored for evaluating investments in electric ships, considering the economic, environmental, and social impacts. Using the Azores as an empirical case study, the results revealed that investing 25 million euros in electric ships yields a significantly positive impact on social welfare (1,906 million euros). For long-distance travel, maritime transport's impact on social welfare is diminished, making it less suitable. Embracing electric ships can unlock new possibilities for enhancing social welfare and sustainability. The contribution of this paper lies in its unique approach, as very few frameworks enable the comprehensive social-environmental valuation of green investments.

Keywords: electric ships; social welfare; sustainable transport; maritime transport; environment; Azores

JEL Codes: Q01, Q56, O18, O22, R53, R58

1 Introduction

Sustainable development is crucial for achieving economic, social, and environmental sustainability. The ultimate objective of sustainable development is to meet present needs while safeguarding the ability of future generations to meet their own needs (World Commission on Environment and Development, 1987). However, the increasing emissions of carbon dioxide and greenhouse gases generate climate change and global warming, posing a significant challenge to sustainable development (Rehman, Ma, Ahmad, Irfan, Traore & Chandio, 2021). Despite efforts to promote sustainable practices, technological innovation, exports, and output continue to exacerbate CO_2 emissions (Dou & Li, 2022). A substantial infusion of green investments is essential to transition towards a low-carbon green economy and facilitate affordable access to clean and renewable energy sources.

Bogacheva and Smorodinov (2017) highlight various barriers that hinder bridging the gap between green economy and investment opportunities. Some of these barriers include poor selection of green projects, management ability, ecological externalities, maturity mismatch, few tools and knowlegde to assess risks associated with green projects, and absence of regulatory and legal frameworks specifically tailored for green finance. To encourage green investments, new financial instruments and policies must be developed (Sachs, Woo, Yoshino, & Taghizadeh-Hesary, 2019).

Transport services are pivotal for driving socio-economic development (Bellizzi, Eboli, & Mazzulla, 2020). In coastal areas and islands, air and maritime transport play a vital role in facilitating mobility for various purposes, including healthcare, education, business, and tourism. However, the transport sector also contributes significantly to pollution, carbon emissions, and other adverse social and environmental impacts (Spagnolo, Papalillo, Martocchia, & Makary, 2012; Viana, Hammingh, Colette, Querol, Degraeuwe, Vlieger, & Aardenne, 2014; Schäfer & Waitz, 2014; Ricardo-AEA, 2014; Daley, 2016). The economic significance of maritime transport has profound implications for the social and environmental dimensions, especially in port regions (Stanković, Marjanović, Papathanasiou, & Drezgić, 2021).

To ensure sustainable development, adopting green and sustainable solutions in the transport sector is imperative (Reisi, Sabri, Agunbiade, Rajabifard, Chen, Kalantari, Keshtiarast, & Li, 2020). Governments, industry players, and remaining stakeholders need to adopt sustainable policies, practices, and solutions to achieve sustainable development in the maritime industry (Essel, Jin, Bowers, & Abdul-Salam, 2022). Nonetheless, imposing mandatory regulations and laws to reduce carbon emissions may raise the cost of travel (Vidović, Šimunović, Radica, & Penga, 2023). To enhance maritime sector decarbonization across the European Union and achieve the carbon neutrality goals of the European Green Deal by 2050 (European Commission, 2019), the European Commission has introduced the FuelEU Maritime program. The main goal is to reduce carbon emissions from the European maritime transport sector (European Commission, 2021).

In recent years, the literature has extensively studied the importance of green infrastructural and transport solutions to enhance sustainability, reduce carbon emissions, reduce independence from foreign energy, and support energy independence, focusing on environmental impacts, technology, technical processes, construction methods, and evaluation models, as stated by Jansuwan, Liu, Song, and Chen (2021) and Lin, Dai, Wang, and Fu (2022).

The literature also presents several relevant case studies. For instance, Melo, Teotónio, Silva, and Cruz (2020) examined the economic value of investing in green road tunnels in Portugal using cost-benefit analysis. Ma, He, Ma, and Xia (2017) presented a case study of green transportation planning in Suzhou Industrial Park, China, using the Analytic Hierarchy Process (AHP). Vukić, Jugović, Guidi, and Oblak (2020) assessed maritime transport routes between China and Central Europe, considering both transport and external costs through data envelopment analysis. Schinas, Ross, and Rossol (2018) proposed a financing model for green ships via export credit schemes, incorporating real data from three major cruise companies. Gore, Rigor-Müller, and Coughlan (2022) investigated the cost-effectiveness of four alternative fuels for maritime transportation in Ireland.

According to Spagnolo, Papalillo, Martocchia, and Makary (2012), adopting new ships with zero environmental impact is feasible. Electric ships present a sustainable alternative to gasoline-powered ships (Hemez, Chiu, Ryan, Sun, Dubrow, & Pascucilla, 2020) and have significant potential in passenger and goods transportation while meeting environmental requirements (Guellard, Montgros, Barriere, Wolfensberger, & D'Oliveira, 2013). Win, Cook, and Davíðsdóttir (2023) found that renewably fueled electric ships exhibit substantially lower externalities. Simona, Silvia, and Paolo (2019) observed the successful use of electric ships in tourist areas across Europe. The authors emphasize critical factors for the success of electric ships, including policies that promote technological advancements and attract sufficient investments through subsidy policies.

Among the various models available to assess green investments, such as cost-benefit analysis (European Commission, 2014; Chaudhuri, Ray, & Ganesh-Kumar, 2018; Forsyth, 2021), Real Option Analysis (ROA) is deemed the most suitable for project valuation under uncertainty and management flexibility to make decisions along the way (Trigeorigis, 1995; Brach, 2003; Mun, 2006; Putten & MacMillan, 2014; Trigeorigis & Reuer, 2017; Zheng & Jiang, 2023). ROA allows for the estimation of the Net Present Value (NPV) for immediate investment and the option value of delaying investment until an optimal time when uncertain factors are resolved.

Vo and Le (2017) explain that uncertainty and irreversibility decrease the incentive for immediate investment and increase the motivation to wait. The uncertainty has been further heightened following the Covid-19 pandemic (Pudney, Mills, & Mudunuri, 2020). Additionally, investment in climate change adaptation and mitigation is characterized by uncertain future payoffs and irreversible costs (Ginbo, Corato, & Hoffman, 2020). Thus, new sources of uncertainty, such as scientific, regulatory, and socio-economic factors, must be considered when evaluating green investments (Heal & Millner, 2014), posing significant challenges in their evaluation and planning.

Given the substantial impacts of investment in electric ships on various stakeholders, including residents, tourists, firms, and the government, a comprehensive valuation framework should incorporate all economic, social, and environmental benefits and costs associated with these stakeholders (Pimentel, Azevedo-Pereira, & Couto, 2012; European Commission, 2014; Couto, Pimentel, & Oliveira, 2022). Although some studies have already assessed investments in the transport sector from a social welfare perspective using ROA (e.g., Couto, Pimentel, & Oliveira, 2022), not all impacts, especially environmental ones, have been fully accounted for. A systematic review of real options studies on climate change adaptation and mitigation conducted by Ginbo, Corato, and Hoffman (2020) revealed that climate-driven uncertainty has not been adequately addressed. Moreover, Davarzani, Fahimnia, Bell, and Sarkis's (2016) review on green ports and maritime logistics literature also revealed that new research should be developed to help practitioners and governments adopt new green solutions for maritime operations.

Singh, Dwivedi, and Pratap (2023) sustain that cost analysis related to maritime decarbonization is a topic that deserves more attention from the literature. Despite the benefits of green solutions and technologies for maritime decarbonization and sustainable development, they usually carry high investment costs, generating conflicting relations between environmental, technological, and economic parameters, which require valuation frameworks to assess their feasibility for multiple stakeholders (Wu, Huang, Wang, Zhen, & Shao, 2023; Vidović, Šimunović, Radica, & Penga, 2023).

To fill this gap, this study introduces a valuation framework for assessing the socio-environmental value of investing in electric ships for short-distance maritime passenger transport from a decision-maker perspective whose goal is to maximize social welfare. The valuation framework incorporates demand uncertainty, represented by a stochastic process with random negative jumps caused by events such as pandemics or extreme environmental occurrences, following recent studies in the ROA field. As a novelty, socio-environmental impacts are integrated, standing the polluter pays principle and making it possible to account for the environmental benefits and costs of electric ships compared to alternative transport modes. The valuation framework is relevant for increasing electric ship investment at the optimal time, enhancing socioeconomic development, maritime decarbonization, and sustainability.

2 Valuation Framework

To assess the social welfare value of investing in electric ships while considering socio-environmental impacts, the frameworks proposed by Pimentel (2009), Pimentel, Azevedo-Pereira, and Couto (2012), Couto, Nunes, and Pimentel (2015), and Pimentel, Nunes, and Couto (2018) are extended. The valuation framework is expanded to include additional social-environmental benefits and costs following the polluter pays principle of the European Green Deal. To account for a specific source of uncertainty, a stochastic process with jumps is incorporated into the model. The primary goal of the valuation framework is to optimize social welfare and enhance sustainability by reducing externalities, allowing optimal decisions from decision-makers whose ultimate goal is to maximize social welfare. The main proposition of this study is that electric ships have a positive impact on social welfare due to environmental cost savings, even considering their investment and operating costs.

The valuation framework assumes that passengers have the option to choose between two transport services for their mobility needs. In this case, air and maritime transport services will be the available options for users. While air transport offers quicker service, it comes with longer boarding waiting times and associated socio-environmental costs. Both air and maritime services may be subject to Public Service Obligations (PSO), with subsidies provided to service providers to reduce travel costs for users.

In this valuation framework, it is implicitly assumed that direct flights between destinations are available. Users have the choice between air and maritime transport, and competition between these modes of transport is considered in the parameters of the stochastic demand process. Passengers will opt for maritime transport if they derive at least the same level of utility as air transport. To maintain similar levels of utility for passengers, economic, environmental, and social impacts generated by each user must be comparable between the two transport services.

The primary source of demand uncertainty is modeled as following a geometric Brownian motion process, which is a standard approach in the Real Options Analysis (ROA) literature. To account for the occurrence of random and unexpected events such as pandemics, economic crises, and extreme environmental incidents, Poisson jumps are combined with the geometric Brownian motion process (see Dixit and Pindyck, 1994):

$$dx_t = \mu_x x_t dt + \sigma_x x_t dw_t + u x_t dn_t \qquad (1)$$

In Equation (1), μ_x represents the demand growth rate, μ_x is the constant standard deviation of the demand growth rates over time. The Wiener process (w_t) has a zero mean and a standard deviation of $\sigma_x\sqrt{dt}$. The process n_t is the Poisson process with a rate of λ_u, and u represents the value of jumps.

The valuation framework takes into account the costs borne by passengers for each transport service (air and maritime), which include travel time, fares, and the associated socio-environmental impacts of each service.

V_0 represents the function value of each passenger for the air transport service (the alternative transport service):

$$V_0(x_t) = m_t - \beta_0 x_t^{\delta_\beta} - \alpha_0 x_t^{\delta_\alpha} - \tau_1 \qquad (2)$$

In Equation (2), m_t represents the disposable income per user at each time, $\beta_0 x_t^{\delta_\beta}$ and $\alpha_0 x_t^{\delta_\alpha}$ represent the functional forms for the value of travel time (VTT) and fare, respectively (following Pimentel, Azevedo-Pereira, and Couto (2012) and related works). τ_1 represents the socio-environmental costs per user.

δ_β is the elasticity between VTT and the demand, while β is the scale parameter linking the two. δ_α is the elasticity, and α is the scale parameter between the fare value and the demand (Pimentel, Azevedo-Pereira, & Couto, 2012).

V_1 represents the function value of each passenger for the maritime transport service using electric ships:

$$V_1(x_t) = m_t + o - \beta_1 x_t^{\delta_\beta} - \omega - \frac{\varphi}{x_t} - \frac{\rho\gamma}{x_t} - \tau_2 \quad (3)$$

In Equation (3), m_t remains the individual disposable income, $\beta_1 x_t^{\delta_\beta}$ represents the functional form for VTT, ω represents the variable operating costs per passenger, γ represents investment expenditures, and φ represents fixed operating costs. The newly introduced variables o, τ_1, and τ_2 were not included in previous related works. o represents the subsidy per passenger, as per the PSO. The subsidy helps offset the operating costs for each passenger. τ_2 represents the socio-environmental cost generated by each passenger using electric ships.

The function V_1 does not include fares because it is assumed that passengers will bear all costs, including the socio-environmental costs, after subsidies. Therefore, the socially acceptable fare is implicitly included and should not be duplicated in the valuation.

In this valuation framework, it is assumed that all impacts will persist on perpetuity. No construction time is involved.

It is expected that τ_2 will be smaller for electric ships compared to regular ships, given their environmentally friendly nature.

To calculate the net benefits generated by electric ships and obtain the opportunity value $v(x)$, the objective function of Ramsey-Koopmans is employed:

$$v(x) = \int_0^\infty e^{-\rho t} E[V_1(x_t) - V_0(x_t)]dt \tag{4}$$

The goal of the model is to find the demand threshold x^* that optimizes investment value and timing. The demand threshold is the one that will maximize $v(x)$. For that, substituting $V_0(x_t)$ and $V_1(x_t)$ on Equation (4) according to Equations (2) and (3), and using dynamic programming techniques presented in the literature (Dixit & Pindyck, 1994; Couto, Nunes, & Pimentel, 2015; Pimentel, Nunes, & Couto, 2018), it is possible to reach the following equation:

$$\begin{aligned} v(x^{\cdot}) = \int_0^\infty e^{-\rho t}[(\beta_0 - \beta_1)E_x(x^{\theta_\beta}) + \alpha_0 E_x(x^{\theta_\alpha}) - \varphi - \rho\gamma - \omega E_x(x) \\ + \tau_1 E_x(x) - \tau_2 E_x(x) + o E_x(x)]dt \\ = \frac{2(\beta_0 - \beta_1)(x^*)^{\theta_\beta}}{2\rho - 2\mu_x\theta_\beta - \theta_\beta^2\sigma_x^2 + \theta_\beta\sigma_x^2 - 2\lambda_u(1+u)^{\theta_\beta} + 2\lambda_u} \\ + \frac{2\alpha_0(x^*)^{\theta_\alpha}}{2\rho - 2\mu_x\theta_\alpha - \theta_\alpha^2\sigma_x^2 + \theta_\alpha\sigma_x^2 - 2\lambda_u(1+u)^{\theta_\alpha} + 2\lambda_u} - \frac{\varphi}{\rho} \\ - \gamma - \frac{\omega}{\rho - \mu_x - \lambda_u u} - \frac{\omega(x^*)}{\rho - \mu_x - \lambda_u u} + \frac{\tau_1(x^*)}{\rho - \mu_x - \lambda_u u} \\ - \frac{\tau_2(x^*)}{\rho - \mu_x - \lambda_u u} + \frac{o(x^*)}{\rho - \mu_x - \lambda_u u} \end{aligned} \tag{5}$$

with

$$\theta_\beta = 1 + \delta_\beta \tag{6}$$

$$\theta_\alpha = 1 + \delta_\alpha \tag{7}$$

Simplifying, the following equation is obtained:

$$v(x^*) = A(x^*)^{\theta_\beta} + B(x^*)^{\theta_\alpha} + C + D + F(x^*) + G(x^*) + H(x^*) + I(x^*) \quad (8)$$

where

$$A = \frac{2(\beta_0 - \beta_1)}{2\rho - 2\mu_x\theta_\beta - \theta_\beta^2\sigma_x^2 + \theta_\beta\sigma_x^2 - 2\lambda_u(1+u)^{\theta_\beta} + 2\lambda_u} \quad (9)$$

$$B = \frac{2\alpha_0}{2\rho - 2\mu_x\theta_\alpha - \theta_\alpha^2\sigma_x^2 + \theta_\alpha\sigma_x^2 - 2\lambda_u(1+u)^{\theta_\alpha} + 2\lambda_u} \quad (10)$$

$$C = -\frac{\varphi}{\rho} \quad (11)$$

$$D = -\gamma \quad (12)$$

$$F = -\frac{\omega}{\rho - \mu_x - \lambda_u u} \quad (13)$$

$$G = \frac{\tau_1}{\rho - \mu_x - \lambda_u u} \quad (14)$$

$$H = -\frac{\tau_2}{\rho - \mu_x - \lambda_u u} \quad (15)$$

$$I = \frac{o}{\rho - \mu_x - \lambda_u u} \quad (16)$$

For economic intuition, let's assign the following meanings to the variables:

- A - travel time savings present value;
- B – fares present value of alternative transport mode;
- C - fixed operating costs present value;
- D - investment expenditure present value;
- F - variable operating costs present value of maritime transport;
- G - socio-environmental costs present value of alternative transport mode;
- H - socio-environmental costs present value of maritime transport;
- I – subsidies present value.

To solve the maximization problem, Ito's lemma can be applied to the opportunity value function $v(x)$, resulting in the following differential equation:

$$\frac{1}{2}\sigma_x^2 x^2 v''(x) + \mu_x x v'(x) - (\rho - \lambda_u)v(x) + \lambda_u v\big((1+u)x\big) = 0, for\ x \neq x^* \tag{17}$$

subject to the following boundary conditions:

$$v(0) = 0 \tag{18}$$

$$v(x) = Ax^{\theta_\beta} + Bx^{\theta_\alpha} + C + D + Fx + Gx + Hx + Ix, with\ x \neq x^* \tag{19}$$

$$v'(x) = \theta_\beta A x^{\theta_\beta - 1} + \theta_\alpha B x^{\theta_\alpha - 1} + F + G + H + I, with\ x \neq x^* \tag{20}$$

As explained by Dixit and Pindyck (1994), Equation (18) is the initial condition, Equation (19) is the value-matching condition, and Equation (20) is the smooth-pasting condition.

The solution for Equation (17), a Cauchy-Euler second-order homogeneous differential equation (Pimentel, Azevedo-Pereira, & Couto, 2012), is as follows:

$$v(x) = a_1 x^h \tag{21}$$

The value h can be obtained analytically using the following expression:

$$\frac{1}{2}\sigma_x^2 h(h-1) + \mu_x h - (\rho + \lambda_u) + \lambda_u (1+u)^h = 0 \tag{22}$$

Using Equation (5) to express a_1, the solution of Equation (17) is given by:

$$v(x) = \big[Ax^{\theta_\beta - h} + Bx^{\theta_\alpha - h} + Cx^{-h} + Dx^{-h} + Fx^{1-h} + Gx^{1-h} + Hx^{1-h} + Ix^{1-h}\big]x^h \tag{23}$$

For a given value of x at $t = 0$, the demand threshold (x^*) required to trigger the electric ship investment for social welfare maximization is determined by numerically solving the following equation:

$$A x^{*\theta_\beta - h}(\theta_\beta - h) + B x^{*\theta_\alpha - h}(\theta_\alpha - h) - C x^{*-h} h - D x^{*-h} h + F x^{*1-h}(1-h) + G x^{*1-h}(1-h) + H x^{*1-h}(1-h) + I x^{*1-h}(1-h) = 0 \tag{24}$$

The opportunity value and NPV for the electric ship investment are expressed as follows:

$$v(x) = \begin{cases} \left(\frac{x}{x^*}\right)^h \left[A x^{*\theta_\beta} + B x^{*\theta_\alpha} + (F+G+H+I)x^* + C + D\right], for\ x < x^* \\ \left[A x^{\theta_\beta - h} + B x^{\theta_\alpha - h} + (F+G+H+I)x^{1-h} + (C+D)x^{-h}\right] x^h, for\ x \geq x^* \end{cases} \tag{25}$$

Following findings from previous authors, the total opportunity value for the electric ship investment is given by the first part of Equation (25). It indicates the value for social welfare if the investment is made at the optimal time.

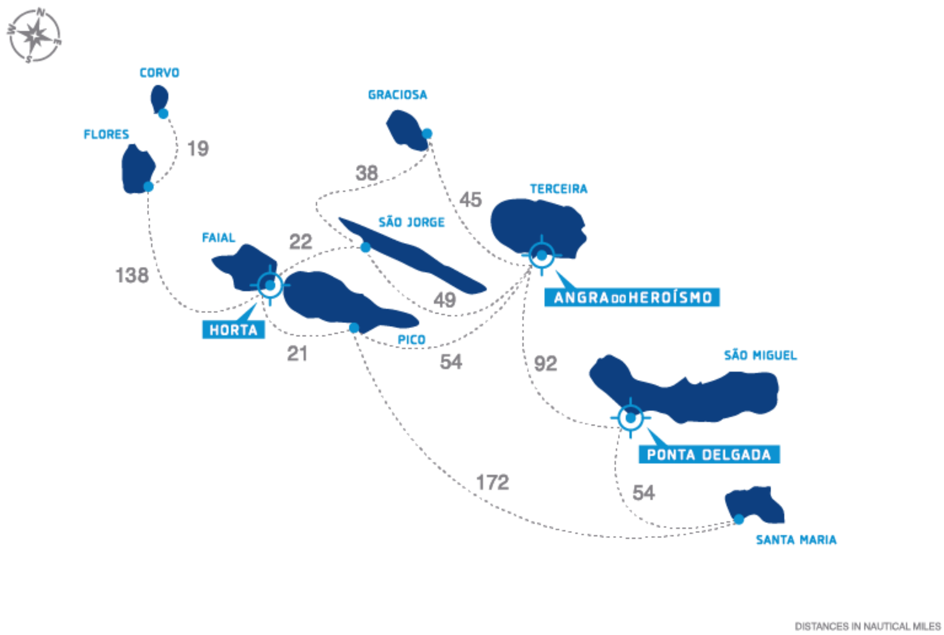
The second part of Equation (25) is the NPV, indicating the value created for social welfare if the electric ship investment is made at t = 0 with the present demand.

The defer option value can be obtained from the difference of both parts. It represents the incremental value of waiting until the demand reaches optimal value.

If the demand is higher than the threshold, the opportunity value equals NPV, and the defer option value is zero, indicating the optimal region where no incremental value can be generated for social welfare.

3 Case Study

The Azores is a archipelago in Portugal consisting of nine islands situated in the Atlantic Ocean between Europe and America (refer to Figure 20). It is composed by three groups: the Western Group, which includes Corvo and Flores islands; the Central Group, comprising Pico, Faial, Terceira, São Jorge, and Graciosa islands; and the Eastern Group, encompassing Santa Maria and São Miguel islands. The Azores has its own Regional Government and is known for its high commitment to sustainability. It holds the distinction of being the first archipelago in the world to be certified as a sustainable tourism destination, in addition to receiving numerous awards recognizing its natural beauty, rich culture, and sustainability efforts (Ponte, Couto, Pimentel, & Oliveira, 2018).



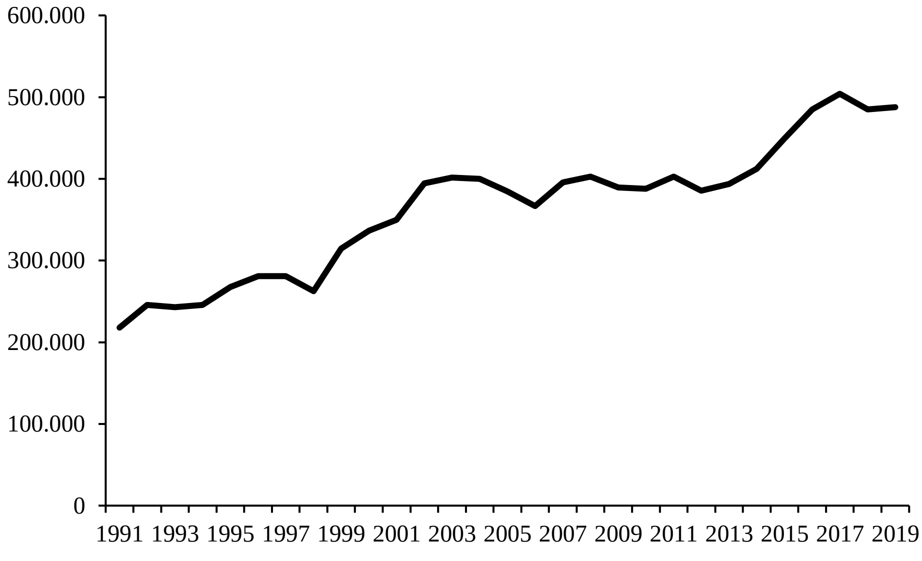
Source: https://sailazores.pt

Figure 1 – Distances (in nautical miles) between islands in the Azores archipelago

To decarbonize maritime transport services and promote sustainability in the Azores, the Regional Government plans to make an investment in two electric ships for passenger transportation between three islands in the Central Group: Pico, Faial, and São Jorge, collectively known as the "Ilhas do Triângulo." These islands are characterized by short distances, with an average of 30.2 kilometers between them.

Inter-island passenger transport is facilitated by both air and maritime transport services. These services are subject to PSO to ensure mobility for residents across the islands, supporting various essential purposes such as economic activities, healthcare, education, business, and family connections. The provision of these services is managed by public regional companies through concession contracts.

Figure 2 illustrates that historical volatility in the region is high, with a noticeable upward trend over time.



Source: Regional Service of Azores Statistics

Figure 2 - Passengers on maritime transport between Pico, Faial, and São Jorge

3.1 Data

The basic parameter values for electric ship valuation from a socio-environmental perspective are listed in Table 1.

Parameter	Value
x_0 – Demand at time 0 for maritime transport	449,072
γ - Investment expenditures (present value)	25 M€
$\beta_0 x_t^{\delta_\beta}$- VTT on airplanes	83.30 €
$\beta_1 x_t^{\delta_\beta}$- VTT on ships	98.26 €
$\alpha_0 x_t^{\delta_\alpha}$- Airplane fare	60 €
φ - Fixed operating costs	5 M€
ρ - Discount rate	5%
μ_x – Demand growth rate	2.3%
σ_x – Demand standard deviation	10.5%
δ_β - Elasticity between demand and VTT	0.43
δ_α - Cross-price elasticity for maritime transport	0.43
ω - Variable operating costs per passenger	0.75 €
o – Subsidy per passenger on maritime transport	59.39 €
τ_1 – Socio-environmental cost per passenger on airplanes	15.59 €
τ_2 - Socio-environmental cost per passenger on ships	0 €
u – Jump value	-0.1
λ_u – Jump rate	0.1

Note: M - Millions

Source: Own elaboration

Table 1 – Parameters values for electric ships valuation

The estimated investment expenditure for the acquisition of two electric ships is 25 million euros, as publicly disclosed by the Regional Government.

Based on historical data on maritime transport between the three islands, the current demand for inter-island flights is 449,072 passengers.

The annual demand growth rate is estimated to be 2.3%, using historical data from 2009 to 2019, which predates the Covid-19 pandemic.

Volatility was computed as 10.5%, following the recommendation of Lewis and Spurlock (2004). This value represents the historical demand volatility during the same period.

Operating costs for maritime transport, including both fixed and variable costs, were estimated using historical financial data from the maritime transport service provider. As the electric ships will not use fuel, fuel costs were excluded from the calculations. Most costs are fixed.

The subsidy per passenger represents the amount paid by the Regional Government to the service provider as stipulated in the concession contract.

The fare for inter-island flights is established by air transport PSO.

The average time per trip, including waiting times, is approximately 111 minutes for airplane travel between the three islands and approximately 79 minutes for ship travel. Although airplane travel is faster, ship trips have shorter waiting times. The value of VTT was estimated considering the average trip times for both modes of transport and the values estimated by HEATCO (2004) for the socio-economic cost of one travel hour in Portugal, adjusted for inflation rates and GDP per capita growth rates.

The socio-environmental cost of air transport is based on estimations by Ricardo-AEA (2014), adjusted for inflation rates. It includes the socio-environmental cost per passenger-kilometer and the environmental impact of landings and take-offs (LTO). The average number of flights required to transport the present demand by airplane was calculated, considering the high negative environmental impact of LTO.

The socio-environmental cost of maritime transport using electric ships is assumed to be zero, following the conclusion of Spagnolo, Papalillo, Martocchia, and Makary (2012) that it is possible to use ships with zero environmental impact. Given that the Azores are increasing the production and use of renewable energies, it is reasonable to assume that the socio-environmental cost of new electric ships will be close to zero.

As data specific to maritime transport is lacking, the elasticity values for both modes of transport follow the data provided by Litman (2010) and Kopsch (2012) for air transport.

The discount rate used is 5%, in line with the recommendation of the European Commission (2014) for relevant projects with an impact on social welfare.

The jump rate and value are set at 0.1 and -0.1, respectively, assuming possible events with a negative impact on demand, similar to the Covid-19 pandemic.

The values of β_0, β_1, and α_0 are obtained through functional forms included in Equations (2) and (3) using the present demand (x_0), following previous related work.

3.2 Results and Discussion

The results of the valuation of electric ships from a social welfare perspective are presented in Table 2. Two scenarios are considered: one with negative demand jumps and another without jumps.

Output	Scenario with negative jumps	Scenario without negative jumps
x^* - Demand threshold	99,232	93,135
$v(x)$ - Opportunity value	1,906 M€	3,714 M€
NPV - Net present value	1,906 M€	3,714 M€
VOD - Value of the option to defer	0 €	0 €

Note: M - Millions

Source: Own elaboration

Table 2 – Electric ships valuation outputs

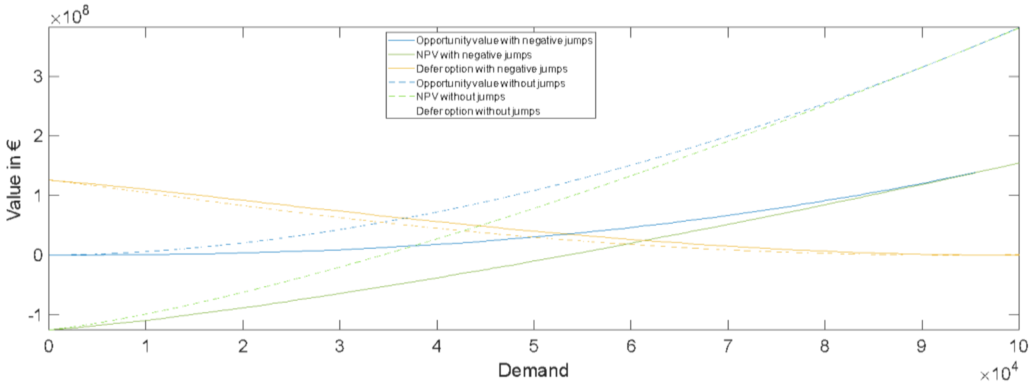
In both scenarios, the positive Net Present Value (NPV) demonstrates the significant positive impact of maritime transport with electric ships on social welfare compared to air transport, taking into account economic, social, and environmental factors, in line with the main proposition of this study. The NPV represents the value created by a 25 million euro investment with the present demand of 449,072 passengers. This value is attributed to the shorter travel times on the three short-distance islands (with smaller waiting times on ship trips compared to airplane trips) and the lower socio-environmental costs associated with maritime transport. The NPV is higher in the scenario without negative jumps, as expected.

The results regarding the positive NPV of alternative ships compared to traditional ships are in line with previous works. For example, Gore, Rigor-Müller, and Coughlan (2022) state the positive NPV for four alternative fuels for maritime transportation in Ireland due to external, carbon tax, and conventional fuel cost saving. Tercan, Eid, Heidenreich, Kogler, and Akyürek (2021) also achieved positive NPV for solar ships.

The opportunity value represents the present value created when the demand is in the optimal region for investment. Since the demand threshold (99,232 passengers for the scenario with negative jumps and 93,135 passengers for the scenario without jumps) is lower than the present demand (449,072 passengers), the opportunity value is the same as the NPV in both scenarios. The trigger for investment is lower in the scenario without negative jumps.

The defer option is 0 in both scenarios, indicating that there is no additional value in delaying the investment in electric ships. The investment option is at-the-money, and no further value is generated by deferring the investment. The demand is in the optimal region in both scenarios, supporting the decision to invest now.

Figure 3 illustrates the opportunity value, NPV, and defer option for different levels of demand in both scenarios.



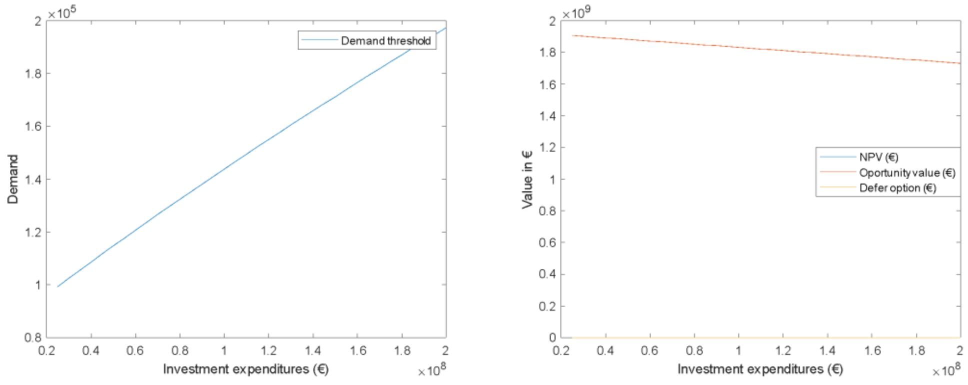
Source: Own elaboration [Print in color]

Figure 3 – Opportunity value, NPV, and defer option value for both scenarios (with and without negative jumps)

In the scenario with negative jumps, the NPV is negative until reaching 53,428 thousand passengers, primarily due to investment expenditures and fixed operating costs. Between 53,428 and 99,232 thousand passengers, there is a positive value for social welfare, but the maximum value is not yet achieved. During this range, there is value in deferring the investment until the demand reaches the demand threshold. The defer option value is positive and decreases as the demand increases. Once the demand threshold is reached, the opportunity value becomes the same as the NPV, and the defer option holds no further value. In these scenarios, it is optimal to proceed with the investment in electric ships.

In the absence of negative jumps, the demand triggers for positive NPV, and the optimal investment timing are smaller.

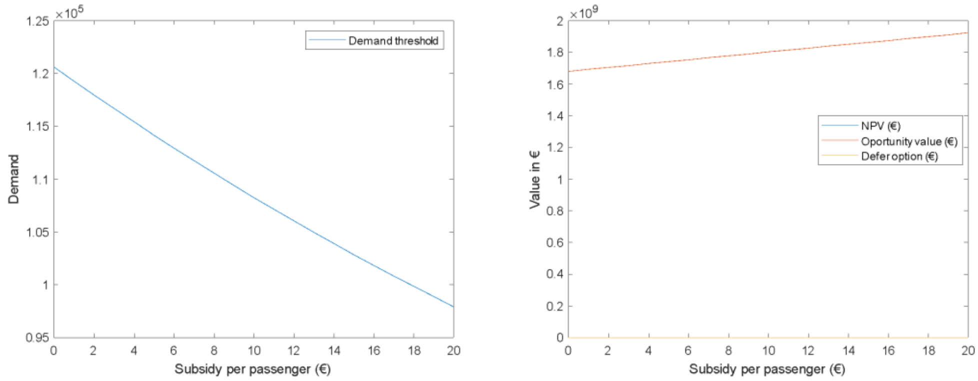
To test the results robustness, sensitive analysis are carried out. The following figures depict the sensitivity analysis of the most significant variables outlined in the framework for the scenario with negative demand jumps and no socio-environmental costs from maritime transport.



Source: Own elaboration [Print in color]

Figure 4 – Impact of investment expenditures (γ)

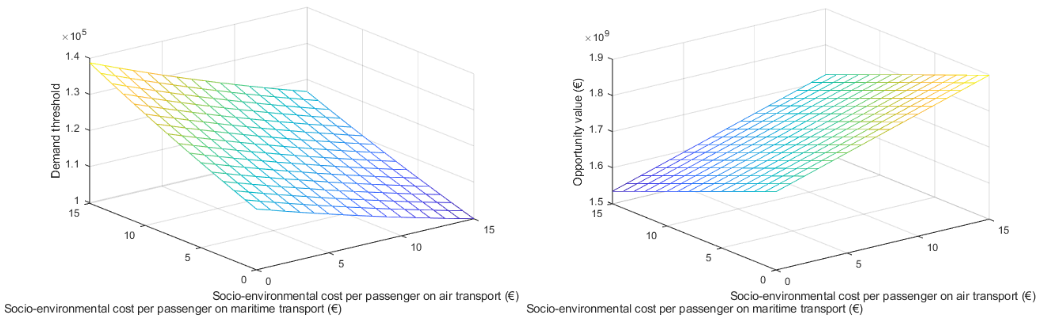
Figure 4 illustrates the impact of investment expenditures (γ). Higher investment expenditures have a negative effect on the demand threshold and opportunity value. As investment expenditures increase, the demand threshold rises while the opportunity value decreases. However, the defer option remains at 0 for investment expenditures ranging from 25 to 200 million euros. This means that the option to deploy the investment is consistently at-the-money, with no additional value gained by deferring the investment.



Source: Own elaboration [Print in color]

Figure 5 – Impact of subsidy (o)

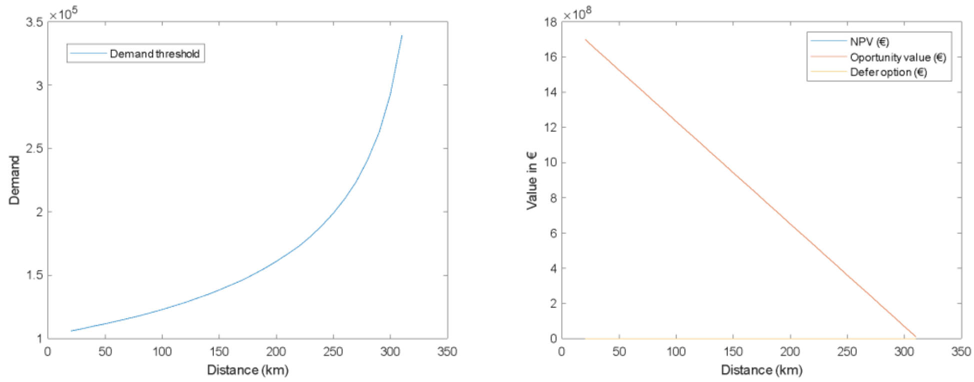
Figure 5 showcases the impact of subsidies on maritime transport (o). Higher subsidies per passenger result in lower demand thresholds. Even in the absence of subsidies, the demand threshold remains lower than the present demand, although the impact on social welfare is diminished.



Source: Own elaboration [Print in color]

Figure 6 – Impact of socio-environmental costs (τ_1 and τ_2)

Figure 6 demonstrates the impact of socio-environmental costs of both maritime (τ_2) and air transport services (τ_1). As anticipated, higher socio-environmental costs result in elevated demand thresholds. Even if the socio-environmental cost of maritime transport is equivalent to that of air transport, the demand threshold remains lower than the present demand due to the time savings associated with maritime transport on short-distance islands (resulting in shorter waiting times). However, it is important to note that a lower contribution to social welfare is observed in this scenario. Electric ships reduce socio-environmental costs, improving sustainability and social welfare. A similar 25 million euro investment on regular ships with $\tau_2 > 0$ will reduce social welfare value creation.



Source: Own elaboration [Print in color]

Figure 7 – Impact of the distance between islands

A sensitivity analysis was also conducted based on the distance between islands. The average travel time per kilometer for each transport service was estimated, taking into account the impact of distance on travel time (β_0 and β_1) and socio-environmental costs (τ_1). Figure 7 demonstrates that as the distance between islands increases, the demand threshold also rises, and at an increasing rate. For an average distance of around 310 kilometers, the opportunity value approaches zero due to the shorter travel time associated with air transport compared to maritime transport.

4 Conclusions

The transport sector plays a crucial role in achieving sustainability and carbon neutrality. Electric ships offer a sustainable alternative to regular ships, reducing fuel consumption and carbon emissions. However, there is a lack of valuation frameworks to assess the impacts of green investments on the economy, society, and the environment. This study addresses this gap by presenting a valuation framework for evaluating a green investment in the transport sector, specifically the acquisition of electric ships for short-distance maritime passenger transport.

Building upon previous works by Pimentel (2009), Pimentel, Azevedo-Pereira, and Couto (2012), Couto, Nunes, and Pimentel (2015), and Pimentel, Nunes, and Couto (2018), this robust framework incorporates new variables related to socio-environmental benefits and costs, as well as subsidies. Unlike most studies in the ROA field, this study adopts a socio-environmental perspective instead of a profit maximization perspective, to improve sustainability and maximize social welfare. The main source of uncertainty in the model is demand, which follows a stochastic process that includes random negative jumps due to unexpected events, such as pandemics or extreme environmental occurrences.

For empirical purposes, the study presents a case study in the Azores. The results demonstrate that investing in electric ships for maritime passenger transport, with zero socio-environmental costs, holds significant value for the short-distance islands in the Azores compared to air transport, sustaining the main proposition of this study. In the context of the Azorean islands, where air transport incurs high socio-environmental costs as the alternative mode of transport, the investment of 25 million euros with a present demand of 449,072 passengers yields a NPV of 1,906 million euros. Furthermore, it is evident that the present demand surpasses the demand threshold (99,232 passengers), and the defer option has no value, indicating that there is no additional benefit in delaying the investment in electric ships. Notably, if negative jumps were not considered, the valuation outputs would be even more favorable, with a demand threshold of 93,135 passengers and a NPV and opportunity value of 3,714 million euros.

The sensitivity analyses conducted on various variables reveal the negative impact of socio-environmental costs on social welfare. A similar investment in regular ships instead of electric ships reduces social welfare value creation. Additionally, maritime transport is not suitable for maximizing social welfare in the case of long-distance travel (over 300 kilometers).

This study contributes to the literature by presenting a ROA valuation framework and an empirical case of valuing a real green investment, addressing gaps identified by previous researchers regarding the impact of green investment decisions on social welfare, the environment, and sustainability. Moreover, it is noteworthy that empirical studies within the ROA field are limited, and their relevance to practitioners and decision-makers is significant, as complex models can be daunting. The inclusion of empirical studies utilizing ROA frameworks can facilitate their practical application.

For industry managers and other stakeholders in the maritime transport sector, particularly public decision-makers in coastal areas and on islands, this study offers a comprehensive framework for evaluating investments in electric ships. It aims to strike a balance between users' utility, economic considerations, social factors, and environmental impacts, thereby facilitating informed decisions on the implementation of electric ships for maritime passenger transportation and promoting sustainable development. ROA frameworks enables control of uncertainty factors, as Rambaud and Pérez (2017) argue, allowing managers and decision-makers in the maritime transport sector to move to adaptive and flexible planning, abandoning passive planning processes, as proposed by Machiels, Compernolle, and Coppens (2020). Furthermore, the results of the case study, based on real data, could offer valuable insights to support the decision-making process on investing in electric ships.

For future research, additional stochastic processes for another variables can be included within the model. Further exploration of optimal subsidies and prices is also warranted. Conducting case studies on green investments aimed at sustainability and decarbonizing various sectors would contribute to empirical knowledge in the field. Additionally, future research can explore new approaches and frameworks tailored to different regions based on data availability.

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