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Article

Investigation of the Viability of Unmanned Autonomous Container Ships under Different Carbon Pricing Scenarios

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Abstract: Autonomous and unmanned shipping are currently trending research topics within the maritime sector, with the promise of a reduction in operating costs and an increase in safety. Although they bring higher investment costs, due to the long lifetime of ships, autonomous ships are expected to bring savings during ship exploitation. This paper aims to analyze capital and operating costs of five different sizes and route length container ships (conventional ships), and under a set of assumptions analyze the same costs for equivalent autonomous ships. A ship cost model is formed, where the typical cost scheme (investment and exploitation costs) is extended by the potential carbon pricing. Carbon pricing is taken into account due to the fact that the design procedure for autonomous and unmanned ships requires the employment of a next-generation regulatory framework. All results indicate the significant economic benefit of autonomous ships over conventional ones. Sensitivity analysis reveals that fuel and emission costs have a great influence on the overall profitability of autonomous vehicles. Although the literature review indicates that reduced operating costs due to crew removal will bring savings for autonomous shipping, results show that savings due reduced operating costs is minor.

Keywords: autonomous shipping; cost assessment; carbon pricing; container ships; *RFR*

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1. Introduction

Nowadays, the shipbuilding and maritime industry are required to continuously improve and upgrade ship safety and environmental performance while reducing overall costs. Autonomous vehicles are already in use in land transport, aviation, military, and chemical industry, and therefore the research community is extremely interested in the development of autonomous ships of various appearances and applications. As one of the most significant research topics of modern marine science, with numerous positive aspects, autonomous ships are expected to gain wider implementation in the near future. Some of the first advantages of autonomous ships that are widely mentioned in the literature are the cost savings and increased safety due to the lower risk of human-induced errors that can lead to human casualties and environmental disasters, as a consequence of reduced crew onboard. Although the cost benefits of autonomous shipping are verified [1,2], the effect of autonomous shipping on the safety of marine transportation is not evident, and considerable research is needed [3]. All fully autonomous vessels monitored and operated remotely, from the shore or another ship, require a high-quality, uninterrupted reliable communication systems, guidance, navigation and control systems as well as data collection equipment [4]. The technologies needed for autonomous shipping already exist, but it is necessary to find the optimal way to implement them in shipping in order to achieve their safety, reliability, feasibility and cost-effectiveness [5]. Significant technology development in sensor and data processing allows autonomous performances. For successful autonomous performance, it is crucial to have a redundant sensor system (e.g., radio detection additionally, ranging (RADAR), light detection additionally, ranging (LIDAR), infrared (IR) cameras, sonars, etc.) [6].

With ship modernization and automation, the number of crew decreased significantly, from approximately 100 crew members in 1900 to 15–26 crew members at the moment on commercial ocean-going ships [7]. Although the number of crew members is constantly decreasing, it is not known whether the number has reached the lower boundary, or with the implementation of autonomous ship crew can be eliminated for most vessels. Apart from human casualties and equipment/vessel damage, maritime accidents may cause environmental disasters [8]. In the period from 2017 to 2021, 53% of maritime accidents were attributed to human error [9]. Jovanović et al. [3] investigated the effect of autonomous shipping on accident occurrence, concluding that although autonomous shipping is most likely to reduce some types of accidents (collision, grounding, contact), due to a lack of onboard crew, in the case of an accident, the consequences will be more severe. A literature review performed by Wrobel [10] to justify the human factor or error effect on maritime safety is widely used in scholarly publications. Wrobel [10] concluded that little evidence has been found within the reviewed sample of literature to support high percentage values (50–80%), and it appears that the figures have not been subject to enough verification. Successful implementation of autonomous vessels will occur when it is proven that they are safer (or at least equally safe), more cost-effective, and more environmentally friendly compared with conventional vessels [10].

The successful implementation of autonomous and unmanned shipping requires significant research and investment. Transport has been a particularly active sector for innovation, due to continuous efforts to reduce carbon emissions. One of the incentives for shipowners to introduce autonomous and unmanned shipping is the introduction of direct carbon allowances in the shipping industry. As a result of policies that incorporate carbon pricing in other industries, innovative low-carbon technologies become more feasible [11]. Carbon pricing, as a potential carbon reduction policy, has been investigated for ship electrification, and it has been concluded that only with the introduction of carbon pricing will battery-powered ships be more cost-effective than diesel-powered ships [12]. The impact of carbon pricing scenarios on real case studies has been investigated in Singapore and China [13,14].

This paper investigates the viability of autonomous container ships by comparing the costs of five vessels of different sizes for a conventional and autonomous operation. For these vessels, the total costs in a period of 20 years are calculated. Emission costs are also accounted for by the scenario-based approach. Under the set of assumptions taken from literature, all costs in a period of 20 years are also calculated for the autonomous equivalent of the selected ships. This paper aims to assess economic impact of autonomous container shipping for different size ships and route lengths. After the introduction, a literature review in autonomous shipping is described, together with trends in container vessel design and operation. Then, the research gap is identified and the contributions of this paper are stated. The classical ship cost model available in the relevant literature is extended with potential carbon pricing and adapted to autonomous container vessel cases. The potential benefits of autonomous container shipping are elaborated upon, and guidelines for future investigations are drawn.

2. Literature Review

2.1. Literature Review of Developments in Autonomous and Unmanned Shipping

The terms "autonomous" and "unmanned" are used in the literature, often to describe the same thing and other times to describe fundamentally different meanings. An autonomous ship is a ship that is controlled by automatic systems both for navigation and engine control [15]. These systems are pre-programmed and can also contain a certain level of artificial intelligence to detect and identify other vessels and perform collision avoidance manoeuvres and path planning, as well as assess situation awareness. An unmanned ship is, as the name implies, a ship with no person on board, but not necessarily autonomous.

Depending on appearance, complexity, and application, a ship could be remotely monitored and operated from a shore control centre (SCC), another ship or mobile device, receiving crucial information via the internet or satellite [15].

At the moment, small autonomous or remotely controlled underwater and surface vehicles are used as research platforms, or measuring or inspection devices [16].

Figure 1 illustrates the expected effect of autonomous shipping on three pillars of sustainability.

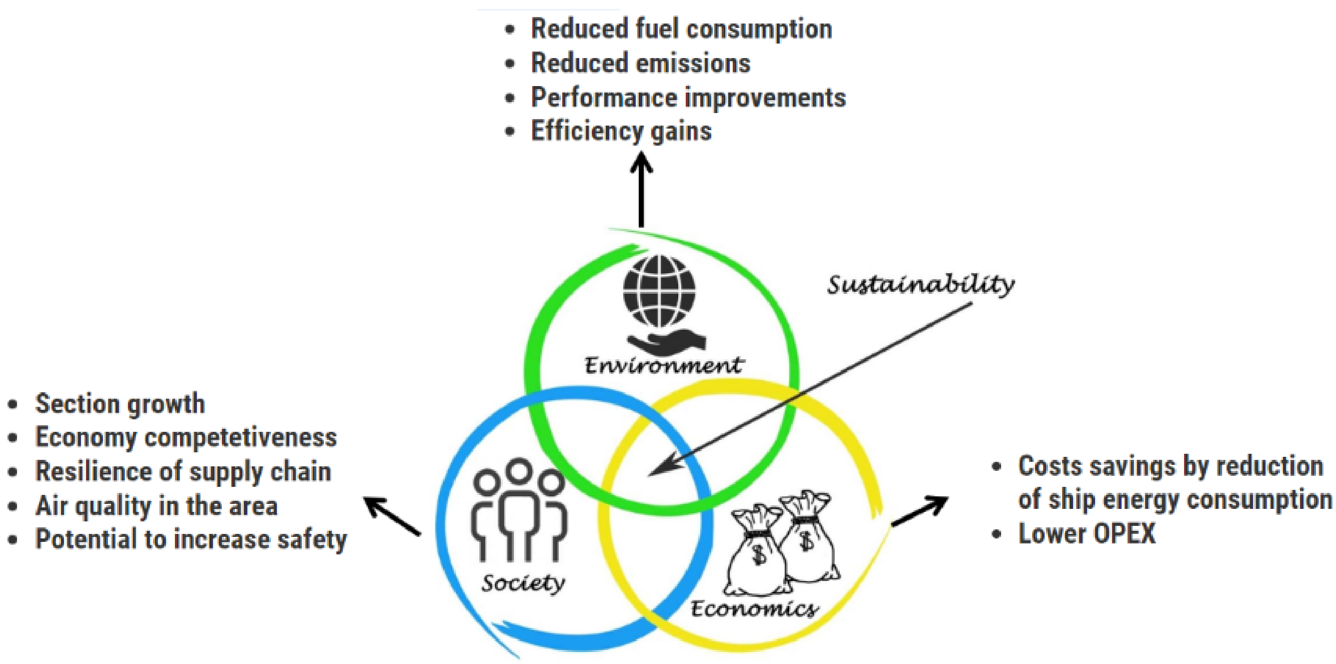

Figure 1. Sustainability of autonomous shipping.

The transition from manned to unmanned and autonomous shipping is expected to be gradual, with a lot of modifications; for this reason, it is important to precisely define levels/classes of autonomy. The International Maritime Organization (IMO) has defined the following four degrees of autonomy (DoA) related to maritime autonomous surface ships (MASS) [17], covering the transition from a ship with automated processes and decision support to fully autonomous ships capable of making decisions and determining actions by itself. The transition phase between these two are remotely controlled ships with and without crew onboard. Progress in the development, testing, and simulations of autonomous and unmanned commercial ships begin in the late 2000s, displaying numerous opportunities for maritime community [18]. Autonomous shipping brings a unique value for addressing many crucial maritime challenges [19]. Research platforms and concepts such as MUNIN [20], Yara Birkeland [21], ReVolt [22] and Rolls-Royce [23] have revealed fundamental differences in the design and technical specifications of autonomous ships, which will have important ramifications on how commercial vessels are designed in the future [24]. It is recommended that the autonomy for fully unmanned ships be constrained, either under supervision or under the control of a shore control centre (SCC) [25]. In Figure 2, the relation between MASS and shore control centres (SCC) is shown.

By analysing 100 maritime accidents involving 119 vessels, Wróbel et al. [26] concluded that with the development of unmanned vessels, the probability of an accident would decrease. However, in the case of an accident, consequences are expected to be more serious than they would be with conventional vessels. Wróbel et al. [27,28] also investigated the safety of remotely controlled and autonomous vessels. Studies indicate that for remotely controlled vessels, controls on technical, regulatory and organizational plains are crucial for successful implementation; meanwhile, for the autonomous vessel, advancement in software development and validation is essential. Using the principle of equivalent safety, de Vos et al. [29] calculated the required subdivision index (the required probability of survival when the flooded condition occurs) for three different sizes of ships, showing that a reduction in the subdivision index is allowed for unmanned ships, and that the reduction will be the greatest for smaller ships. After determining the risk factors of remotely controlled MASS without a crew onboard, Fan et al. [30] proposed a framework for risk and safety analysis that may assist the process of design of MASS and shore control centres (SCC). Utne et al. [31] identified multiple different operational states that change depending on autonomy level, and each has different risks that need to be managed.

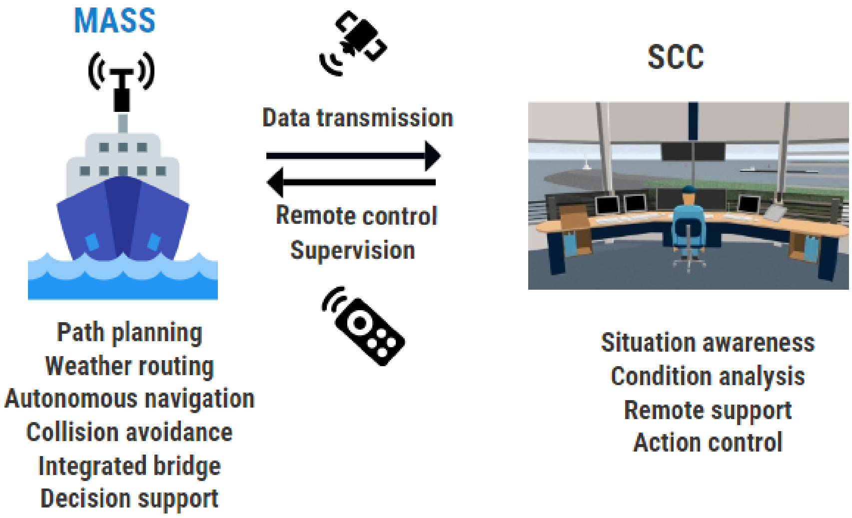

Figure 2. Relationship between MASS and shore control centres (SCC).

It is also important to consider the possibility of cyber-attacks, taking into account the need for an undisturbed connection between the vessel and shore control centre (SCC). A method for cybersecurity risk assessment is given in [32], outlining the importance of intrusion detection systems and redundancy in communication.

Waterborne autonomous guided vessels (AGVs) show great potential for usage in inter-terminal transport (ITT) in large and busy ports, as they are labour-cost-free, can perform reliably 24/7 and comply with the development of smart ports. Zheng et al. [33] propose closed-loop scheduling and control of AGVs for ITT, and demonstrate its effectiveness with simulation results.

The economic and environmental benefits of autonomous short-sea shipping are outlined in [34], with the electricity and methanol-powered ship showing the best results from both points of view. Jiang et al. [35] proposed, developed, and tested a novel three-body 11,000 m rated autonomous and remotely operated vehicle. Previous research is mainly focused on collision avoidance [36–38] and path planning [39,40] with research in autonomous shipping economic feasibility currently lacking.

The driving force for the development of unmanned and autonomous ships lies within the following opportunities:

1. Costs savings in the reduction of ship energy consumption, and lower operating and voyage costs that making ships more environmentally friendly;
2. Safer waterborne transport by ruling out crew-related mistakes that lead to an extensive number of accidents;
3. A competitive industry with the opportunity to grow in size and volume; and
4. Employment of personnel onshore through the creation of engaging and exciting maritime jobs [41,42].

2.2. Literature Review of Developments in Container Shipping

Container transportation has a major role in the global shipping industry, globalization and the world's economy. Containerization has enhanced trade between nations, efficiency in port operations and technological progress, and encouraged a competitive economic environment. Recent statistics show that containerized trade increased almost five times from 64 million tons in 2000 to 266 million tons in 2019 [43]. This demonstrates the increasing role of container transportation and its contribution to the global economy.

An increase in the size of a container ships is constant due to the increase in demand and the economies of scale accomplished by the employment of larger ships. Taking into consideration that container mega-ships use hub-and-spoke networks, and ordinary container ship multi-port-calling networks, Imai et al. [44] concluded that container mega-ships are more cost efficient.

In more recent studies, Malchow [45] showed that lower costs diminish after enhancement in size over 21,000 *TEU* because of an increase in draught, beam, and port time, resulting in higher port costs. As ship size increases, the cost per *TEU* decreases; however, handling time per *TEU* is higher after a certain size [46]. The link between size and operations is outlined in the study by Sys et al. [47], according to which optimal ship size depends on the transport segment (deep-sea vs. short-sea shipping), terminal type, trade lane and technology. Based on the dimension of existing ships from Loyd's database, further development of container ships is predicted, and we can conclude that an increase in capacity has the greatest impact on beam dimensions, while length and draught change slowly [48].

The impact of a hub-and-spoke network with mother and daughter routes is studied and compared with the current feeder network by Msakni et al. [49], revealing that a significant cost reduction comes with split pickups and deliveries. Talley et al. [50] provided a model for evaluating the port's service chain effectiveness and quality. They displayed the port cost functions that can be used as port performance indicators.

The method for examining optimal speed in container shipping is obtained by comparing daily shipping costs at different speeds [51]. Speed reduction (slow steaming) reduces fuel consumption and thus reduces emissions. The effects of slow steaming on bunker costs, service quality and shipping time are provided by Lee et al. [52].

The energy efficiency design index (EEDI), a technical measure for new ships, encourages the use of more energy-efficient (less polluting) equipment and engines [53,54]. Moreover, EEDI represents a technical measure of energy efficiency, and refers to the ratio of the released amount of carbon dioxide (CO_2) to the benefit to society (e.g., tonne mile of cargo transported) [55]. By analyzing CO_2 emissions from container ships from 2006 to 2017, Pierre et al. [56] estimated a decrease of 33% in annual emissions on a worldwide scale, stating that advances in ship technology and slow steaming most contributed to the emission reduction. Ammar and Seddiek [57] studied the best methods for the improvement of energy management of large container ships.

For the improvement of air quality close to ports, IMO established emission control areas (ECAs) in the North American, US Caribbean, North Sea and Baltic coastal areas, where the emission requirements are stricter. Within these areas, sulphur in the fuel oil is limited to 0,10% [58]. The establishment of ECAs requires ship usage of low-sulphur fuels, which increases voyage costs, thus having a great impact on sailing patterns and strategy. Li et al. [59] analysed ships' response strategy to ECAs with fuel switching strategy and its environmental benefits. Despite the potential emission reduction in ECAs, due to the re-routing of a considerable number of vessels, especially smaller ones, overall benefits are diminished [60].

2.3. The Aim and Contributions of the Paper

Based on the literature review presented in Sections 2.1 and 2.2, knowledge gaps are indicated as follows:

- Research is lacking on the economic impact of unmanned autonomous container ships, as studies dedicated to autonomous ships mainly consider navigation, communication, and sensor systems.
- To the best of the authors' knowledge, there are no studies that simultaneously consider autonomous shipping and different carbon pricing scenarios for container vessels. Consequently, neither the environmental benefits nor the economic potential of autonomous shipping are clear for marine applications. However, these aspects are very important, as the goal of increasing ship autonomy appears simultaneously with future emission reduction targets and cannot be ignored.
- To the best of the authors' knowledge, no studies offer a comparison of the costs of different size unmanned autonomous container ships.

This paper investigates the economic aspects of different size autonomous unmanned container ships where different fuel and emission pricing scenarios provided by World Energy Outlook are used. Bearing in mind that autonomous ships are mainly in the research and development stage, an extensive sensitivity analysis of the results is conducted.

This paper aims to investigate a pathway for the modernization of the container shipping sector, leading to the reduction of ship lifetime costs and emissions by increasing the level of ship autonomy. Nowadays, reducing emissions in the marine sector and increasing the level of ship autonomy are among the most important research topics where container shipping should be addressed.

The contributions of this paper are summarized as follows:

- Development of a cost model for different size autonomous container vessels which includes different carbon pricing scenarios.
- Comparison of all costs for five different size container ships with their equivalent autonomous alternatives.

Identification of dominant factors that influence the economic feasibility of autonomous shipping.

3. Methodology

The cost scheme, Figure 3, is acquired from Stepford [61] and adapted for the considered problem. It classifies costs into two categories:

- Capital or investment costs; and
- Operating (exploitation) costs involved in the day-to-day running of the ship, such as crew, administration, stores, insurance and maintenance costs. In addition, expenses related to specific route, such as fuel cost, port charges, canal dues and emission cost, are included.

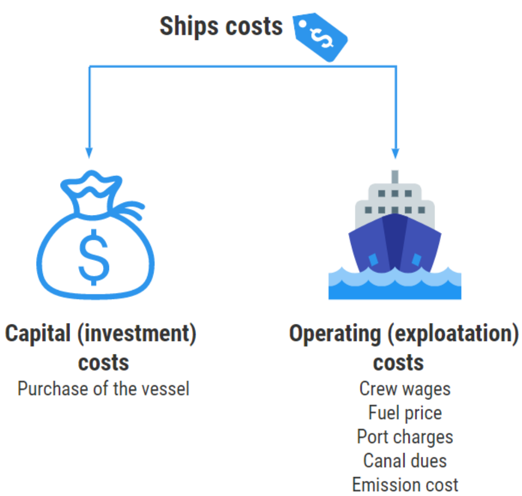

Figure 3. Ship cost model.

In the following subsections, the differences in capital and operating costs between conventional (manned) and autonomous (unmanned) ships, and their effect on costs, are described.

3.1. Capital Costs

Capital costs include the purchase of the vessel. Reduction or elimination of the crew in autonomous shipping will affect the value of the ship. Removing the hotel system will affect ship design, reduce lightship weight and increase the ship's cargo capacity. Vessels will be no longer bound to minimum sight restrictions from the bridge. Possible design changes on the deckhouse will reduce air resistance and thus increase fuel efficiency. Due to the implementation of innovative technologies that will replace human operators (sensors, actuators, communication systems and software), stricter monitoring requirements and redundancy of systems, capital costs will increase. New elements like the shore control centre (SCC) will also contribute to increased costs [62,63].

3.2. Operating Costs

Crew costs depend on the size and competence of the crew; thus, by increasing ship autonomy, the crew number decreases. Even for ships where the total number of crew is not reduced, technologies intended for reducing the crew can enable the employment of less qualified crew, which requires lower wages and therefore reduces costs. For ships with reduced or no crew, costs related to shore control centres (SCC) must be considered. To gain cost benefits, the total crew cost required to support operations onboard and onshore must be taken into consideration [62,63].

Daily operating costs C_{dop} are calculated according to Equation (1) obtained from [64], where ship size represents container capacity in *TEU*:

$$C_{dop} = 267 \cdot (ship\ size)^{0.4}. \tag{1}$$

Operating costs increase throughout vessel lifetime. Annual operating costs are calculated as follows:

$$C_{op} = C_{dop} \cdot (1 + \delta)^{(i-1)} \cdot T, \tag{2}$$

where annual growth rate δ of 1.3% is used for calculating operating costs in 20 years of exploitation time i, and T is operating time in a year (days).

The voyage costs of a ship are variable costs linked to a specified route, such as fuel cost, port dues, canal fees, pilotage, etc. No hotel system and changes in design bring out reduced air resistance and reduced lightship weight that will decrease fuel consumption. Savings related to reduced fuel consumption have the greatest impact on the viability of autonomous ships. Port fees are expected to increase due to autonomous ships changing port infrastructure regarding cargo handling, mooring, docking and undocking. New infrastructure will be needed for canals, thus increasing their fees. New variable costs related to transferring information between autonomous ships and shore control centres (SCC) will depend on the amount of transferred data and carrier (satellite, internet, etc.) [62,63].

The annual voyage costs C_{Voyage}, Equation (3), including annual fuel consumption cost C_{Fuel}, annual port costs C_{Port}, and annual emission cost $C_{Emission}$ [65]. In this paper, the emission cost represents the carbon expenses of the conventional and autonomous vessel, respectively, for different carbon pricing scenarios. The annual voyage costs (C_{Voyage}) are calculated according to the following equation [64]:

$$C_{Voyage} = C_{Fuel} + C_{Port} + C_{Emission}. \tag{3}$$

N (number of trips in a year) is calculated as follows [64]

$$N = \frac{T}{t} \tag{4}$$

where T is operating time in a year and t is total vessel round trip time. Fuel cost C_{Fuel} are calculated [64]

$$C_{Fuel} = N \cdot \alpha \cdot p, \tag{5}$$

where α is daily fuel consumption and p is a fuel price. Port cost C_{Port} consists of port disbursement account C_{PDA} and canal fee C_{canal}. Port costs are calculated as follows [64]:

$$C_{Port} = N \cdot (C_{PDA} + C_{canal}). \tag{6}$$

Emission Costs

The Paris Agreement, adopted by 195 nations in December 2015, aims to cut emissions in 2050 to half of 2005's levels [66]. Currently, in the shipping sector, there are no direct emission taxes; however, there is a set of regulations prescribing a gradual decrease in ship emissions. The carbon credit should be seriously considered for future ship designs [67]. Carbon credit costs are calculated by interpolating the forecast values of the carbon allowance (CA) [67], and are shown in Figure 4. Each CA refers to a permit to emit 1 ton of CO_2 emission [68]. The considered scenarios are as follows [67]:

- Stated policies scenario (STEPS), which includes only the firm policies that are in place or have been announced by countries;
- Announced pledge case (APC), a variant of the STEPS that assumes that all of the net zero targets announced by countries around the world to date are met in full; and
- Net-zero emissions by 2050 scenario (NZE), which describes how energy demand and the energy mix will need to evolve if the world is to achieve net-zero emissions by 2050.

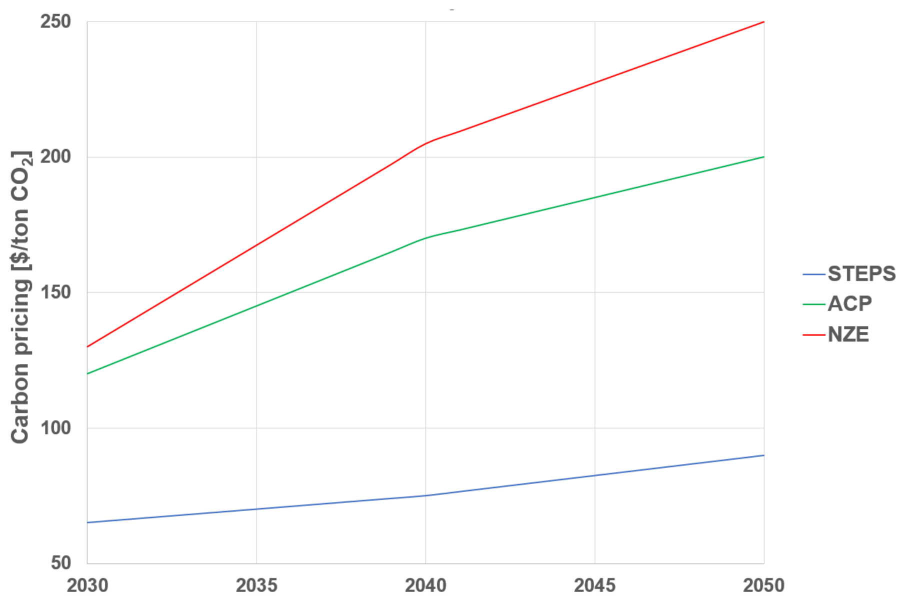

Figure 4. Carbon pricing scenarios.

Emission costs are calculated by the following equation [13]:

$$C_{Emission} = \sum_{i=1}^{20} \alpha \cdot EF \cdot CA_i, \tag{7}$$

where α is daily fuel consumption, EF is CO_2 emission factor and CA_i is carbon pricing for a year i. EF for heavy fuel oil is 3114 (g/kg of fuel) [69]. Fuel prices are also taken for different scenarios and illustrated in Figure 5.

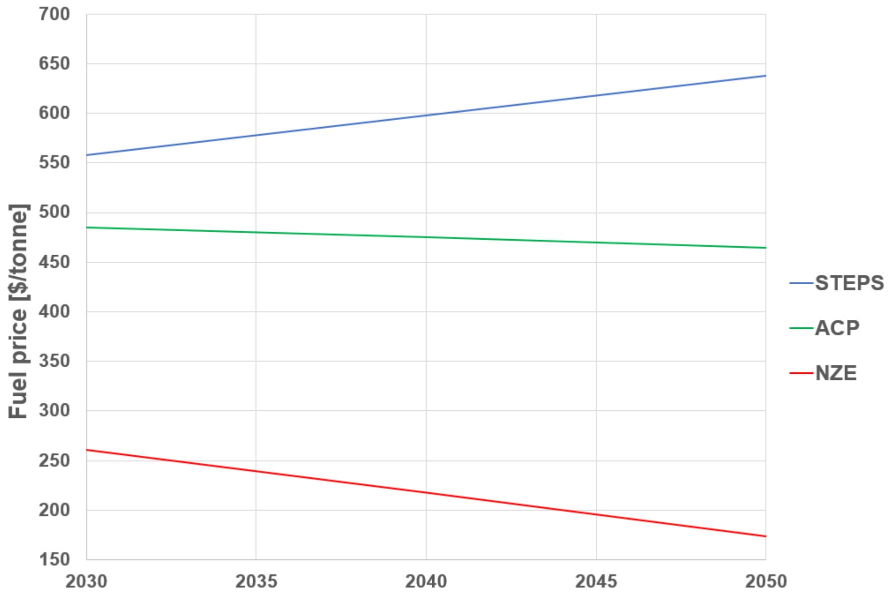

Figure 5. Fuel pricing scenarios.

As can be seen in Figures 4 and 5, all three scenarios assume that with time, carbon pricing will rise, while fuel price will lessen, except for fuel price in the STEPS scenario. These policies serve as initiatives for the development of advanced and greener technologies, and autonomous and unmanned shipping should also be considered within that context.

3.3. Daily Costs

In order to observe the economies of scale and compare results for different size ships, daily costs and daily costs per TEU are calculated for all ships, using the following equations:

$$C_{daily} = \frac{\sum_{i=1}^{20} \frac{C_{op_i} + C_{Voyage_i}}{(1+r)^i} + C_{inv}}{20 \cdot T}, \tag{8}$$

$$C_{daily_{TEU}} = \frac{C_{daily}}{TEU}, \tag{9}$$

where T is operating time in a year and r is the return rate of 10%.

3.4. Required Freight Rate

The required freight rate (RFR) per container is calculated by summing the annual average cost of operating and owning a ship and dividing it by TEU, as presented in the following equation:

$$RFR_i = \frac{C_{op_i} + C_{Voyage_i} + C_{inv}}{TEU}. \tag{10}$$

RFR_i is the required freight rate in specific year. With an RFR calculation, the problem of predicting revenue is avoided. There are several ways of carrying out this calculation, but all aim to show which ship design will give the lowest unit transportation cost within the parameters specified by the owner. It is left to the investor to weigh up whether the project has a reasonable chance of earning enough revenue to cover expenses.

4. Results and Discussion

In this paper, an economic analysis of conventional and autonomous power systems of five container ships of different sizes is performed. The assumptions are as follows:

- Conventional and autonomous ships are equally safe;

- Routes, speed, and time spent in ports are the same for the conventional and autonomous ships; and
- All five ships sail round trip between two ports.

Costs are calculated for the conventional vessel, and appropriate changes in costs are used for calculations for the autonomous vessel. In Figure 6, the selected vessels and shipping routes are presented. Vessel technical data and routes are obtained from [70] and presented in Table 1.

Figure 6. Selected vessels and their shipping routes [70].

Table 1. Selected vessels and technical data [70].

Ship Name	Bianca Rambow	Maersk Montana	CMA CGM Rigoletto	One Mackinac	Marit Maersk
Deadweight (t)	11,286	61,499	114,004	146,867	214,733
Length (m)	134	292	349	366	399
Beam (m)	23	32	43	52	59
Draught (m)	7.5	13	12	15	15
TEU	862	4544	9415	13,900	18,270

Costs are calculated for the typical routes of all five vessels. Operating time in a year is assumed to be 320 days. Port dues are obtained from [71], the Suez Canal fee from [72], and distances between ports from [73]. The sailing duration between ports is calculated for a speed v of 20 knots. Crew costs are obtained from [64]. The newbuilding price is calculated using a regression model developed in [65]. Data used for the calculation costs of the conventional vessel are presented in Table 2.

Table 2. Data used for calculating costs of the conventional vessel.

Ship Name	Bianca Rambow	Maersk Montana	CMA CGM Rigoletto	One Mackinac	Marit Maersk
TEU	862	4544	9415	13,900	18,270
Newbuilding price (mil. $)	30.28	55.32	88.44	118.94	148.65
Daily fuel consumption (t)	34.2	88.94	126.98	158.19	180.48
Daily manning costs ($)	805.42	2418.55	3045.75	4496.64	5910.34
Port dues ($)	600	3042	6468	9210	11,694
Suez Canal transit fee ($)	-	-	441,642.37	547,323.05	742,677.47

For autonomous vessels, data collected through the project MUNIN and published in [62] is used to calculate the costs of unmanned autonomous vessels. Within operating costs, crew wages and crew-related costs are deducted. By taking into consideration new equipment and rent, wages for personnel in the shore control centre (SCC) are added, which correspond to 133,400 $ per year. It is estimated that fuel consumption for autonomous ships is reduced by 10%, taking into consideration reduced air resistance, lower lightship weight and lack of hotel system [62,74]. Port calls are approximately 20% higher for autonomous vessels [62]. The overall production cost of the autonomous vessel is defined as 10% higher than of the conventional vessel price [62]. For 13,900 and 18,270 *TEU* container vessels, which are twin-island, as there is no crew onboard, minimum visibility from the bridge is not mandatory. This increases their capacity, 13,900 *TEU* by 5.2%, and 182,700 *TEU* by 3.9% [75]. Fuel consumption is used for calculating CO_2 emissions which are converted to daily emission costs per container for three scenarios in Figure 7. Figure 8 illustrates the daily fuel cost per *TEU* for three scenarios. In further text abbreviation, C stands for conventional while A for the autonomous vessel.

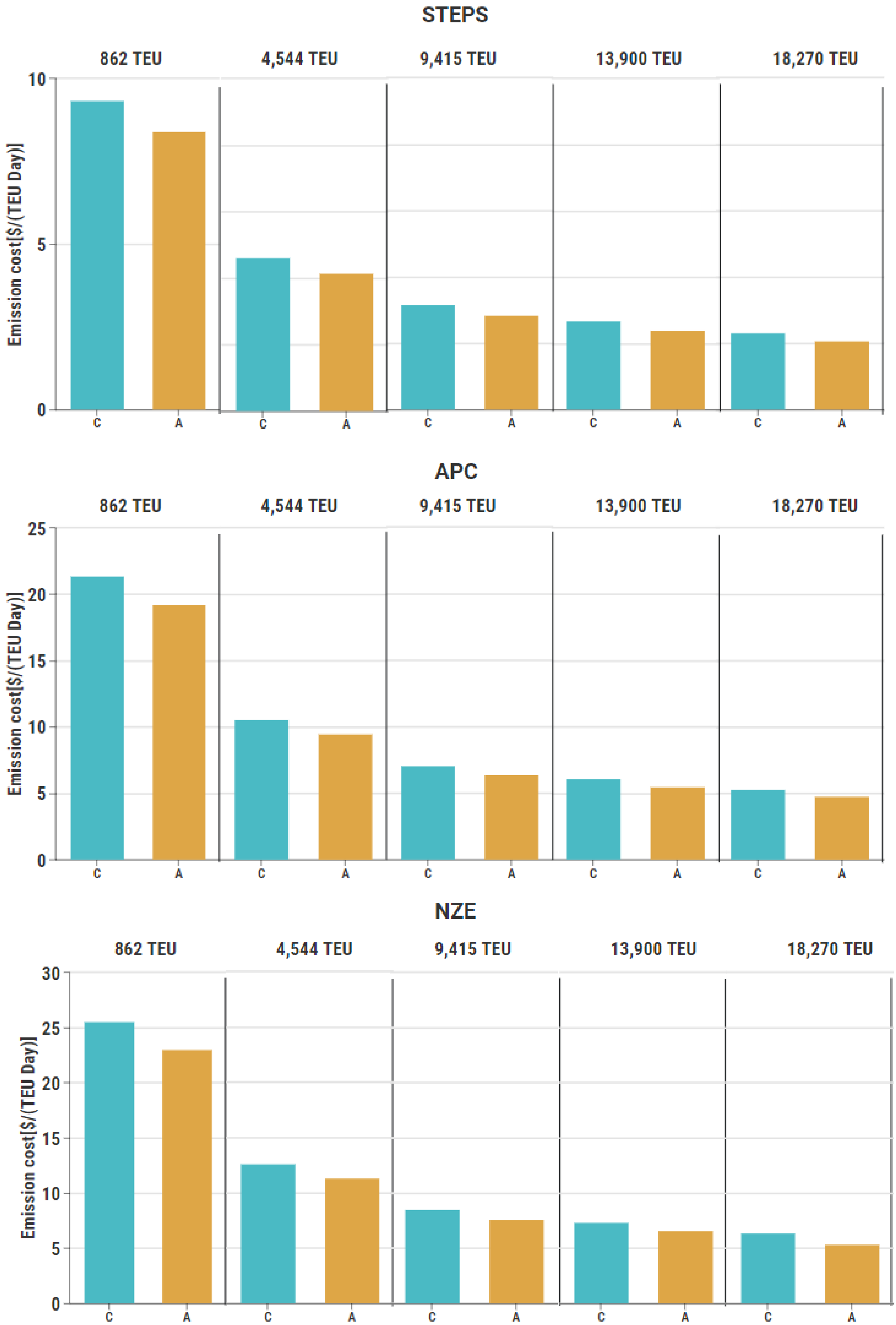

Figure 7. Daily emission costs per container for STEPS, APC, and NZE scenarios for the year 2040.

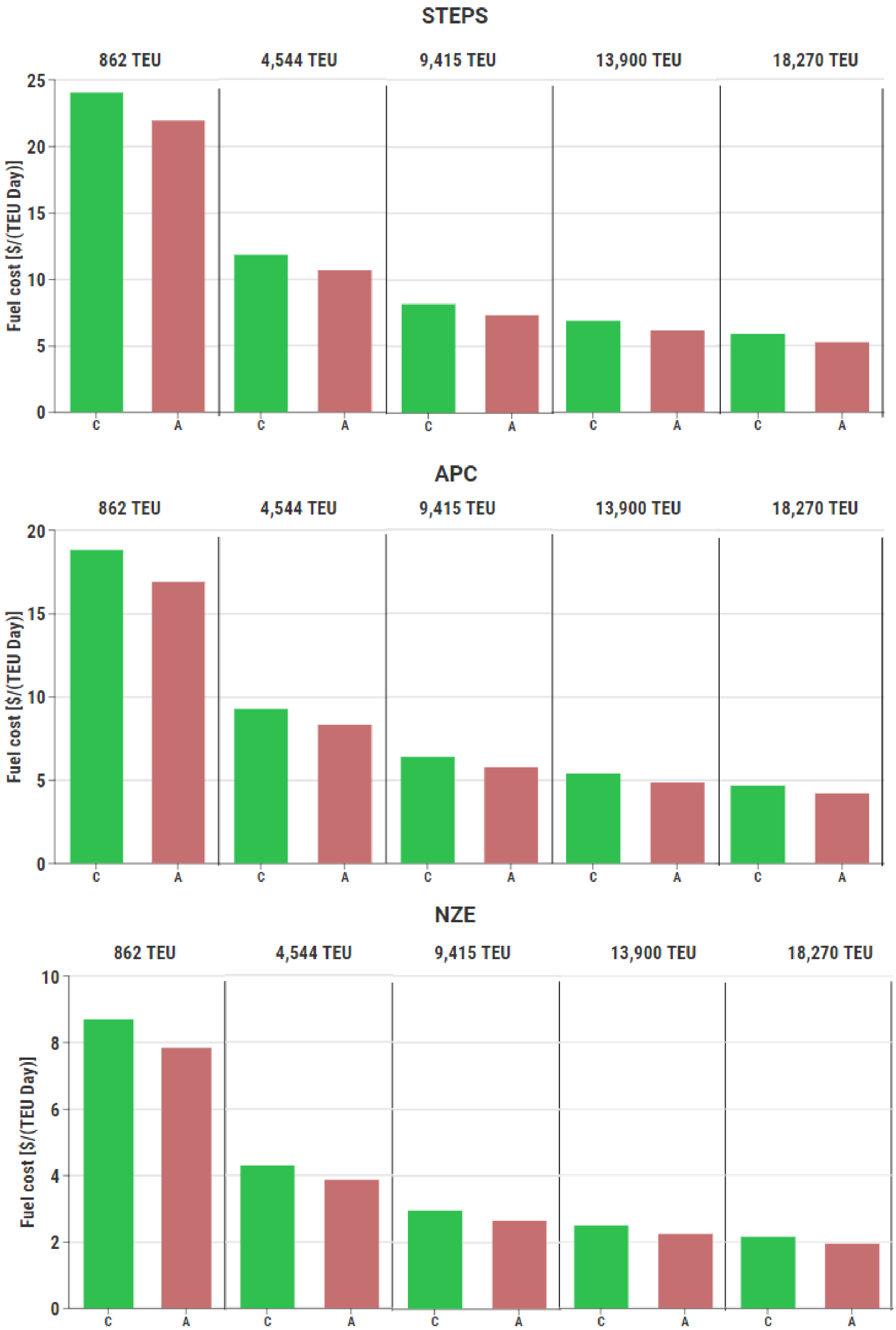

Figure 8. Daily fuel costs per container for STEPS, APC, and NZE scenarios for the year 2040.

Daily emission and fuel costs are calculated for the representative year of 2040. Daily emission and fuel costs, calculated for all five conventional and autonomous ships for STEPS, APC, and NZE scenarios, indicate that economies of scale occur with an increase in ship capacity. That means that overall daily costs per unit decrease with an increase in ship capacity. Autonomous ships have lower daily costs for all ships and scenarios.

After obtaining all costs of owning and operating the vessel, the total daily costs of a ship and daily costs per container for the conventional and autonomous vessel are calculated and presented in Figures 9 and 10. Emission and fuel costs are calculated for the STEPS scenario.

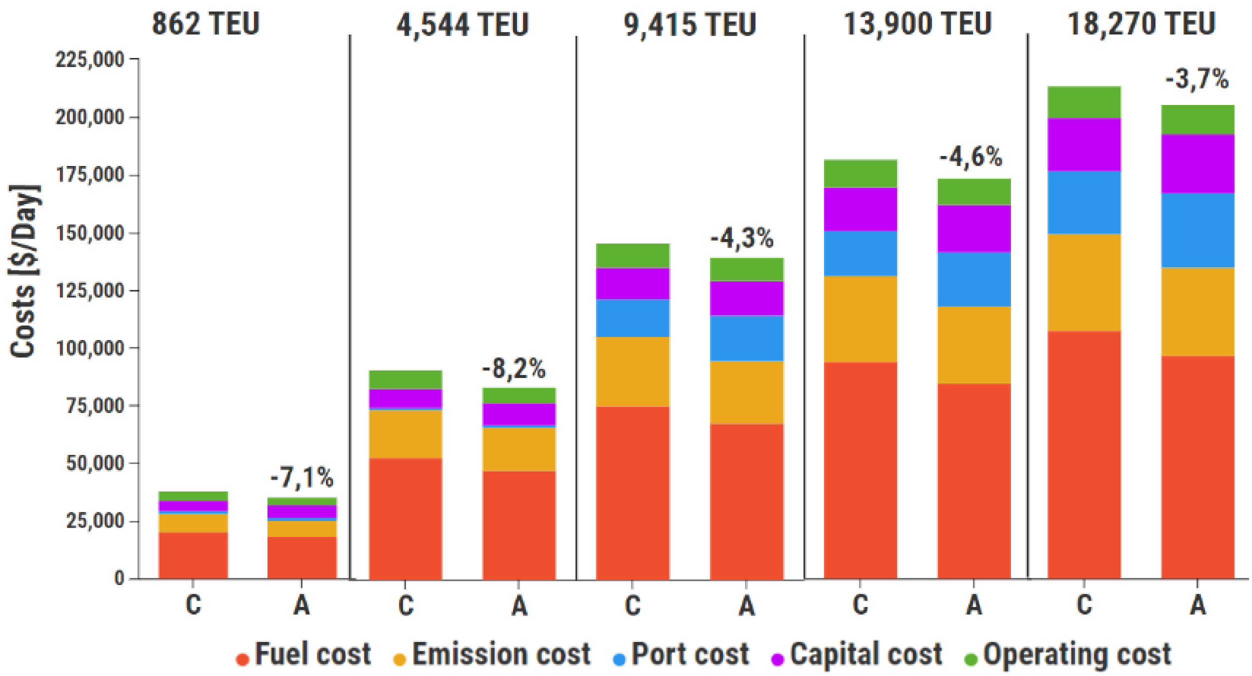

Figure 9. Daily costs of conventional and autonomous vessels.

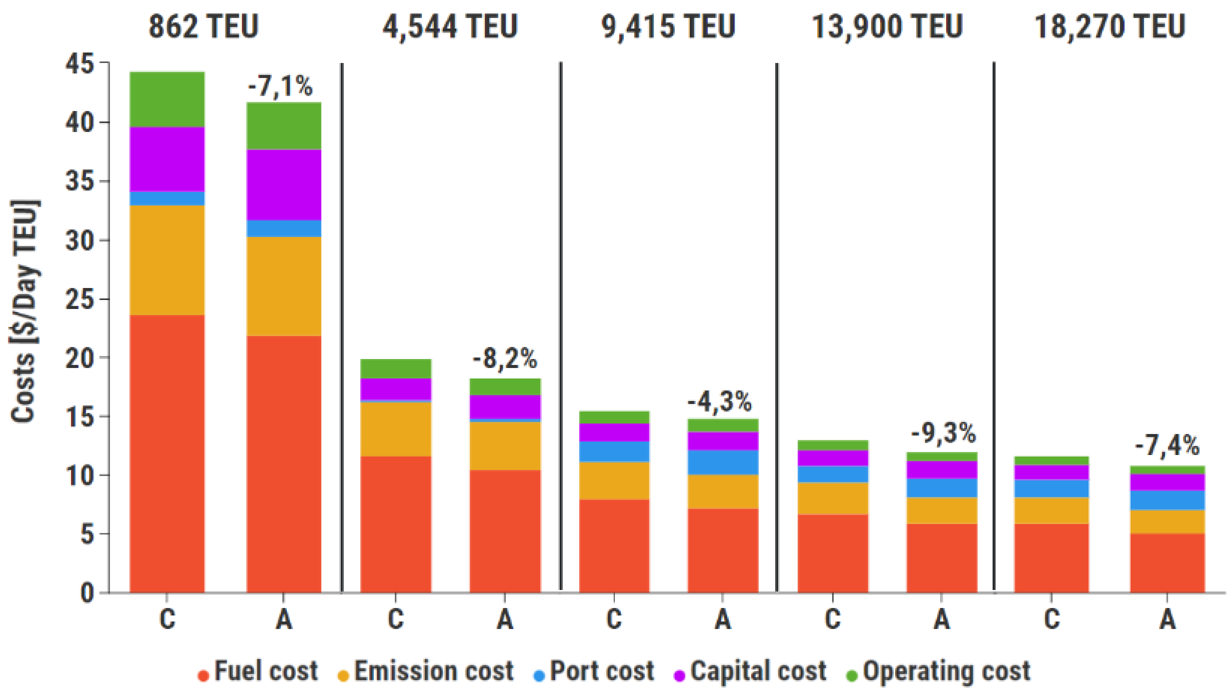

Figure 10. Daily costs of conventional and autonomous vessels per container.

For all five vessels, significant savings occur for the autonomous option, where fuel and emission costs have the greatest impact on total costs. Due to decreased fuel consumption in autonomous shipping, potential savings arise. Autonomous vessels also have lower operating costs; however, port and capital costs increase. In Figure 10, economies of scale for the container ship are obvious, demonstrating that with an increase in capacity, cost per unit decreases. In Table 3, the *RFR* for the representative year of 2040 for all five conventional and autonomous ships is given.

Table 3. *RFR* of conventional and autonomous ships for year 2040, with and without emission costs.

Vessel	***RFR* ($)**			***RFR* ($)$_{no\ Emission\ Costs}$**		
	C	**A**	**Diff.**	**C**	**A**	**Diff.**
862 *TEU*	44.3	41.14	−7.1%	34.96	32.73	−6.4%
4544 *TEU*	20.03	18.08	−8.2%	15.42	13.93	−9.7%
9415 *TEU*	15.52	14.86	−4.3%	12.34	12	−3%
13,900 *TEU*	13.09	11.87	−9.3%	10.41	9.46	−9.1
18,270 *TEU*	11.7	10.83	−7.4%	9.37	8.74	−6.7%

RFR is lower for autonomous vessels, indicating the viability of autonomous shipping. Economies of scale for container ship are evident, demonstrating that with an increase in capacity, *RFR* per unit decreases. However, this does not necessarily mean that the largest ships are the most suitable for autonomous applications. *RFR* is also calculated for the case in which there is no emission pricing.

A sensitivity analysis of *RFR* is performed by changing some of the key input values (fuel costs, emission costs, port costs, capital costs and operating costs). Figure 11 shows sensitivity results for both conventional and autonomous vessels.

Sensitivity analysis results are shown in three groups. The first group shows together the three smallest ships (862, 4544, 9415 *TEU*), followed by the second group (9415 and 13,900 *TEU*), and the third (13,900 and 18,270 *TEU*).

Among the six parameters, *RFR* shows the highest sensitivity to changes in fuel costs, followed by emission costs. The impact of changes in the input values of capital is that operating and port parameters are much more modest, with almost the same values.

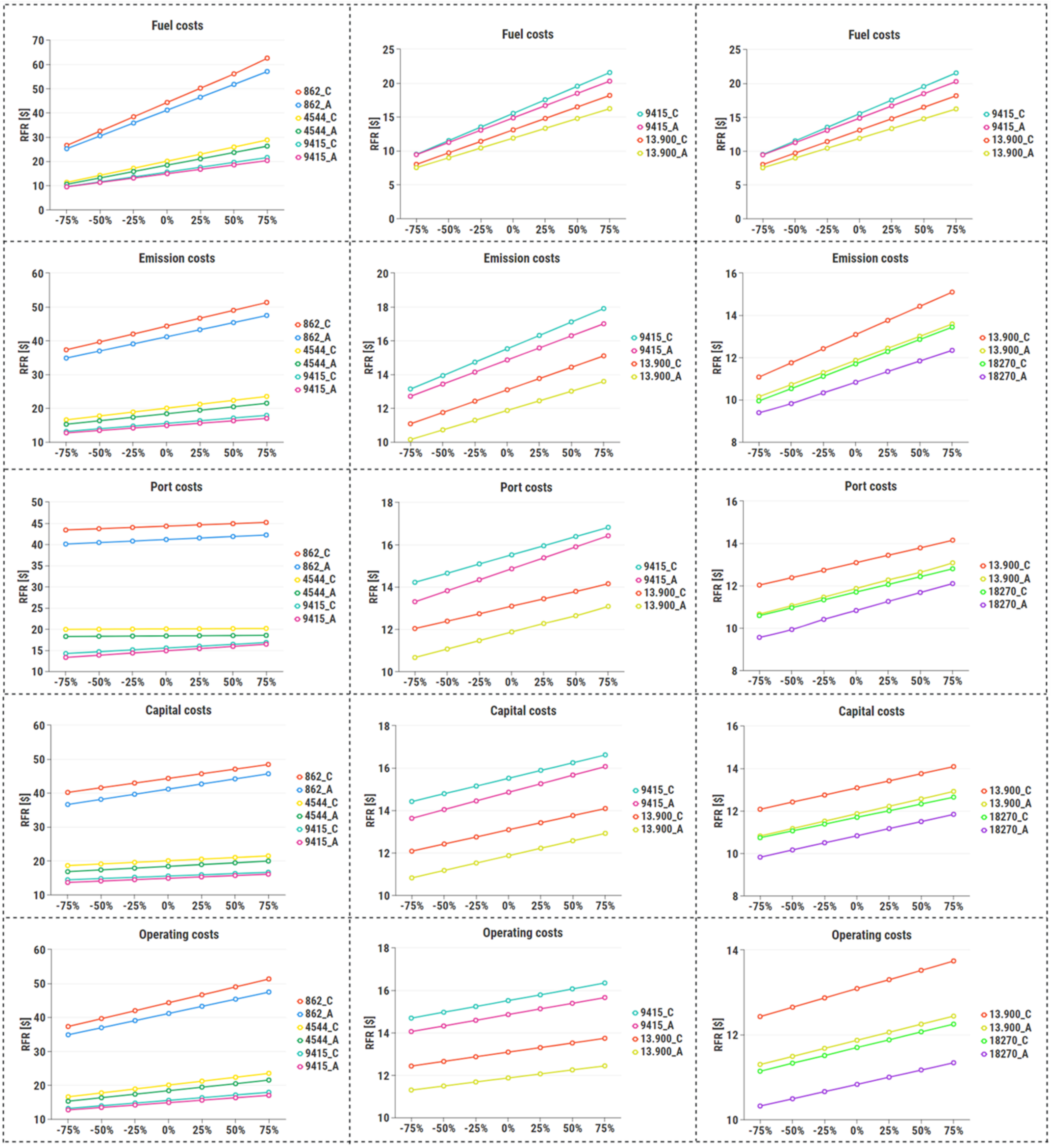

Figure 11. Sensitivity analysis of *RFR*, for the year 2040, for the conventional and autonomous vessel.

5. Conclusions

In this paper, cost analysis of owning and operating five container ships with different loading capacities is performed for both conventional and potential autonomous vessels. Taking into consideration changes in operating, voyage, and capital costs for both vessels, total daily costs, daily costs per container, and *RFR* for the representative year are calculated. A sensitivity analysis of *RFR*, focusing on five parameters, is presented to check the robustness of the results.

The main findings of the performed research are summarized as follows:

- With a stricter emission taxes scenario, the difference in costs between a conventional and autonomous vessel becomes more significant;
- Economies of scale occur in daily costs per container, as well as in daily emission and fuel costs per container;
- Autonomous vessels have lower fuel consumption, resulting in lower fuel and emission costs;
- Operating costs decrease in autonomous shipping, and port and capital costs increase, but total costs are lower for autonomous vessels;
- *RFR* is lower for autonomous shipping, and when ship capacity is over 10,000 *TEU*, *RFR* stabilizes for both conventional and autonomous ships;
- reduced fuel consumption in autonomous vessels is the greatest benefit of autonomous shipping; however, considering that some other less complex and undeveloped technologies (e.g., alternative fuels, hybrid propulsion, waste heat recovery and energy saving devices) also offer similar gains, this standalone benefit is not sufficient to justify research and development of autonomous ships.

From an economic point of view, gains due to the reduction of operating costs in autonomous shipping as a result of the removal of the ship crew are not significant; fuel costs are most influential. Further research should include a combination of autonomous shipping and hybrid or alternative powering options. Although results indicate that container ships with larger capacities are more feasible, these should be taken with caution, because the relationship between the autonomous ship manoeuvrability from shore control centre (SCC) and ship size has not been investigated enough. Some limitations regarding the cost model used in this paper should be kept in mind. Firstly, the costs are calculated assuming that conventional and autonomous vessels use the same fuel and operate at the same speed. Secondly, changes in insurance costs regarding autonomous shipping are not taken into consideration. Thirdly, time spent in port is assumed to be the same for both types of vessels; however, taking into consideration that there is no crew onboard an autonomous vessel, maintenance performed in ports should increase time spent in port.

For this analysis, a container ship is chosen because of its simplicity in comparison with other types of vessels. Since this investigation considers only container vessels, further research should include other types of vessels in order to evaluate the economic benefits of autonomous shipping at the global fleet level. Future research should build on these results and further investigate the implementation of alternative fuels and renewable energy into autonomous shipping, and changes in port and canal infrastructure for the accommodation of autonomous vessels. The presented model can serve as the basis for the investigation of autonomous ships with more complex design and operative features, such as short-sea vessels, where a more complex cost-assessment scheme will be needed.

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Nomenclature

Variables		Abbreviations	
C	Cost ($)	AGV	Autonomous Guided Vessel
CA	Carbon allowance price ($/ton CO_2)	APC	Announced Policies Scenario
EF	Emission factor for CO_2 (g/kg fuel)	COLREGS	Convention on the International Regulations
i	Number of years		for Preventing Collisions at Sea
N	Number of round trips per year	DoA	Degree of autonomy
p	Fuel price ($/ton)	ECA	Emission control area
r	discount rate (%)	EEDI	
RFR	Required freight rate ($)	IMO	International maritime organization
T	operating time in a year (days)	IR	Infrared
t	total vessel round trip time (days)	ITT	Inter Terminal Transport
v	average ship speed along the route (knots)	LIDAR	Light detection and ranging
Greek symbols		MASS	Maritime autonomous surface ship
α	daily heavy fuel consumption (tons/day)	MUNIN	Maritime unmanned navigation through for Preventing Collisions at Sea
δ	Annual growth rate	NZE	Net-Zero Emissions by 2050 Scenario
		RADAR	Radio detection and ranging
		SCC	Shore control centre
		STEPS	Stated Policies Scenario
		TEU	Twenty-foot equivalent unit

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