Aalborg Universitet

The economic and environmental viability of green and autonomous ships in inland shipping ecosystems

Kloch, Kristoffer; Kristiansen, Jimmi Normann

Published in:
Journal of Physics: Conference Series

DOI (link to publication from Publisher):
10.1088/1742-6596/2867/1/012030

Creative Commons License
CC BY 4.0

Publication date:
2024

Document Version
Publisher's PDF, also known as Version of record

Link to publication from Aalborg University

Citation for published version (APA):
Kloch, K., & Kristiansen, J. N. (2024). The economic and environmental viability of green and autonomous ships in inland shipping ecosystems. *Journal of Physics: Conference Series*, *2867*(1), Article 012030. https://doi.org/10.1088/1742-6596/2867/1/012030

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy
If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

Downloaded from vbn.aau.dk on: March 18, 2026

Journal of Physics:
Conference Series

PURPOSE-LED PUBLISHING™

PAPER • OPEN ACCESS

The economic and environmental viability of green and autonomous ships in inland shipping ecosystems

To cite this article: Kristoffer Kloch and Jimmi Normann Kristiansen 2024 *J. Phys.: Conf. Ser.* **2867** 012030

View the article online for updates and enhancements.

You may also like

- NTNU Shore Control Lab: Designing shore control centres in the age of autonomous ships
Ole Andreas Alsos, Erik Veitch, Leander Pantelatos et al.
- Analysis on Design Scheme of Autonomous Ship Cooperative Control
Mei Jing and Weigang Zheng
- Steering towards sustainability: the impact of autonomous shipping on achieving sustainable development goals
Anastasia Tsvetkova, Krzysztof Wróbel, Andrei-Raoul Morariu et al.

This content was downloaded from IP address 130.225.247.88 on 17/03/2025 at 10:08

The economic and environmental viability of green and autonomous ships in inland shipping ecosystems

Kristoffer Kloch*[1,2] and Jimmi Normann Kristiansen[3]

[1] Innovation & Partnerships, DFDS, Copenhagen, Denmark
[2] Department of Sustainability and Planning, Aalborg University, Aalborg, Denmark
[3] Business School, Aalborg University, Aalborg, Denmark

*E-mail: krkl@plan.aau.dk

Abstract. This paper explores the potential of using green, autonomous ships in revitalising inland shipping in Europe against the backdrop of declining market share and the dominance of "economy-of-scale" in waterborne freight transportation. It assesses the economic and environmental viability of converting freight from road- to waterborne modalities in broader business ecosystems, specifically along the Rotterdam-Ghent corridor. The analysis leverages operational and commercial insights from logistics firms, ports and terminal operators, combined with data on European goods flows by road, and accounts for operational, financial and environmental variables including realistic scenario building and ecosystem implications. Findings indicate that inland shipping in general and green, autonomous shipping in particular offer both economically and environmentally viable alternatives to road transport. The study calls for further research into green, autonomous ships from an ecosystem perspective as a potential solution to current challenges in sustainable freight transportation.

1. Introduction

Sustainable maritime transportation is seen by many as a significant component in global development, economic growth, and social equity [1]. Therefore, the European Union (EU) is actively working towards converting freight transportation from road to water [2]. Road transportation both entails higher environmental costs produced by the freight vehicles themselves as well as significant societal costs associated with road transportation in general [3] [4]. This includes, but is not necessarily limited to, amplified road congestion, poor air quality, increased risk of accidents and related disturbances of logistical arteries in the road network that impacts both businesses and citizens. Despite the environmental and societal advantages of maritime transport, waterborne freight faces challenges as both short sea and inland shipping has lost market shares in the European transport industry over the past decade [5] . This may partly be a consequence of the prevailing "economy-of-scale" paradigm that has reduced transport costs for waterborne transportation by building increasingly larger ships, while concurrently straining existing infrastructure and decreasing supply chain resilience [6]. The Ever Given grounding in the Suez Canal in 2021 or the Dali collision with Baltimore’s Francis Scott Key Bridge in 2024 are recent examples of this, both of which resulted in major disruptions across supply chains [7] [8].

Emerging research suggests that small, green, autonomous ships may offer significant cost savings and environmental benefits that have the potential to challenge the current paradigm

Content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

while simultaneously increasing resilience and the heterogenous use of logistic hubs [9] [10]. However, in their recent literature review on the costs and benefits of autonomous shipping, Ziajka-Poznanska & Montewka [11] concludes that valid financial models of autonomous shipping are lacking and that there is a significant amount of uncertainty affecting the cost estimates in present studies on the matter. Similarly, Tsvetkova & Hellström [12] investigate how and for whom autonomous ships are beneficial across the different actors in the maritime logistics ecosystem and conclude that in order to fully realise the value of autonomous ships, one must transcend beyond the existing operational structures in the industry and investigate the new business models that are enabled. This echoes the study by Ghaderi [13], who finds that although current research may highlight the potential economic benefits of autonomous vessels for ship operators, it overlooks potential cost transfers to other supply chain actors upstream and/or downstream from the autonomous vessel. Furthermore, present studies on autonomous ships often compare these to their conventional counterpart instead of the roadborne alternatives in line with the EU's ambition of converting freight from road to sea (see e.g. [14] [15] [16]). For these reasons, this paper provides a detailed, holistic analysis of inland autonomous ships in the broader logistics ecosystems they inhabit, including the economic and environmental implications to other actors within said ecosystem. First, the economic and environmental viability of already existing vessel types was explored to create the baseline from which, second, the potential implications brought about by electrification and autonomy could be investigated. The paper can thus be considered an investigation of both traditional and autonomous ships on the inland waterways from a logistics ecosystem perspective.

2. Methodology

The study seeks to explore the economic and environmental viability of autonomous ships on the inland waterways as a competitive alternative to truck transport in Europe. The attractiveness of the competing solutions is calculated using insights from logistics firms combined with previous research, official information and public registry data. The viability is based upon exhaustive investigation of price structures for logistics services in combination with extensive data on cargo flowing between the regions of Rotterdam (The Netherlands) and Ghent (Belgium), filtering and analysing the cargo volumes, types, and transport characteristics to propose economic implication in the broader logistics ecosystem based on potential cargo conversion scenarios.

In line with Ziajka-Poznanska & Montewka [11], Tsvetkova & Hellström [12], and Ghaderi [13], the study first outlines the commercial interests involved in the logistics ecosystem around hinterland logistics. Such interests are scoped to logistic actors only and does not include manufacturers, underwriters etc. Figure 1 provides a high-level overview of the entire transport chain from an incoming, seagoing vessel to a final point of arrival, including the actors involved in the ecosystem as well as their activities, capital expenses, operational expenses and revenue streams. This is in line with ecosystem research, emphasising the need for multiple wins for an appropriate transformation of business models herein [17]. The same chain would apply for export activities from an original port of departure to an outgoing, seagoing vessel.

For a potential ship service to be attractive in the long term, it is presupposed that the relevant logistics actors in the ecosystem would need an acceptable financial, environmental and/or operational benefit of the new transport setup, assuming that all operators in the chain are classical, for-profit organisations with overall ambitions anchored around such type of benefits. For the actors to either directly or indirectly cocreate a viable and sustainable business ecosystem, a balance must be struck where all participants benefit from their involvement.

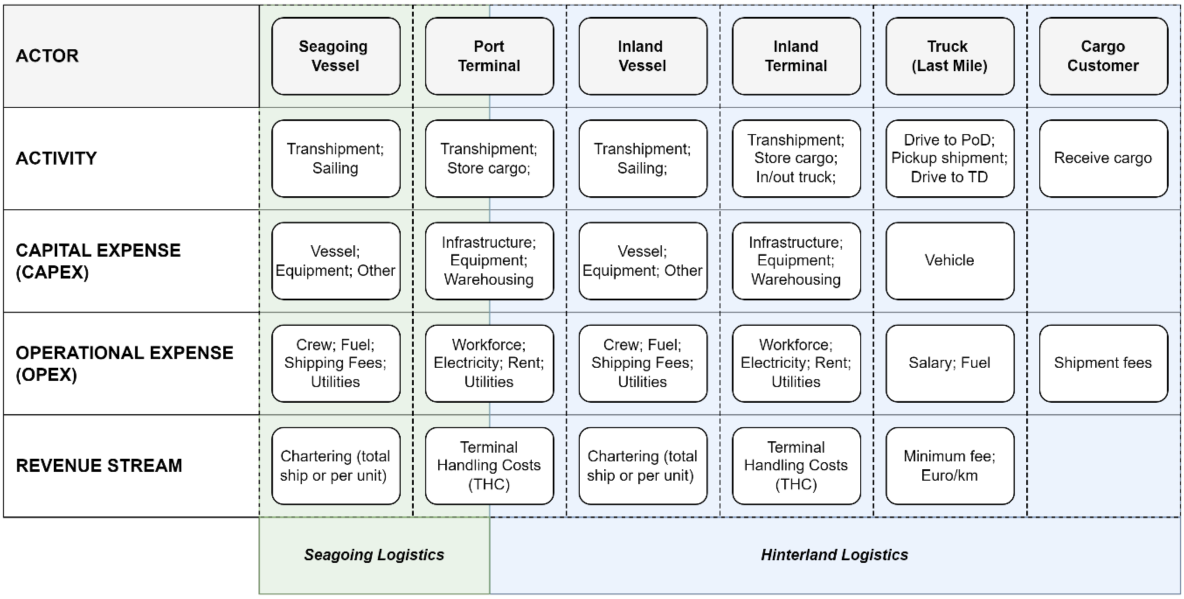

Figure 1 Business ecosystem for hinterland logistics on inland waterways

2.1 Route characteristics

The specific corridor chosen for investigation runs between Rotterdam and Ghent due to its strategic importance for logistics companies, manifested in ongoing developments such as the Seine-Scheldt expansions [18]. Today, freight transport between Rotterdam and Ghent is conducted via truck and via barge, although the latter is more often the exemption than the norm. Through the use of online tools such as EuRIS [19], interviews with logistics firms and analysis of various maps, a route for both the barge and the truck was determined. These are visualised in Figure 2 and characterised in Table 1. These have been used as the point of departure for building the scenarios and, consequently, the economic modelling and the business ecosystem in question.

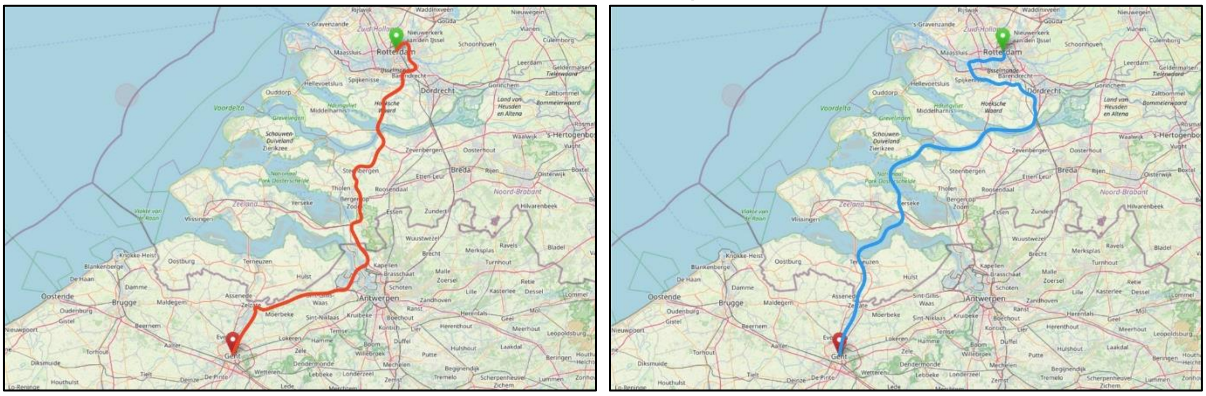

Figure 2 Truck (left, red) and barge (right, blue) transport options on the Rotterdam - Ghent corridor

Table 1. Route characteristics of this study

Route	Distance	Speed	Locks	Time per lock	Last mile distance	Last mile speed	Ops./day (man.)	Ops./day (aut.)
Barge	160 km	10 nm/h	4	45 min	50 km	50 km/h	18 h	24 h
Truck	200 km	80 km/h	N/A	N/A	N/A	N/A	10 h	24 h

2.2 Vessel and truck characteristics

Given that <8% of the total road transport volume is containerised [20], shifting cargo from road to water in a containerised, Lift-On-Lift-Off (LoLo) solution would necessitate a larger change of the transport equipment on road or, alternatively, the additional price of converting containerised units on the barge to trailerised units for last mile via cross-docking. For a trailerised, Roll-On-Roll-Off (RoRo) solution, this would however not be necessary, as up to 92% of relevant road volumes could be targeted. Staying agnostic to the type of cargo unitisation on the barge, the study includes two hypothetical solutions, one LoLo and one RoRo, based on the Sendo Liner XL LoLo concept [21] and the AEGIS Use Case B RoRo concept [22] respectively. The competing roadborne transport solution is based on a Volvo FH, being a standard long-haul freight truck on the market. The economic parameters of both barge and truck options have been established primarily from interviews with logistics firms. Table 2 and Table 3 show the physical and the economic characteristics respectively of these concepts.

Table 2. Physical characteristics for vessel and truck solutions used in this study.

Type	Model/Size	Deadweight [a]	Length	Width	Capacity
LoLo barge	CEMT VI	5,118 t	135 m	14.2 m	176 units (4 layers)
RoRo barge	CEMT VI	5,118 t	139 m	15.0 m	69 units (2 layers)
Truck	Volvo FH16	26 t	7.13 m	2.50 m	1 unit

[a] Deadweight for both barge solutions is based on the Sendo Liner XL concept

Table 3. Economic characteristics for vessel and truck solutions used in this study.

Type	Chartering price	Minimum price	Minimum charter
Barge	5,000 € per day	5,000 €	1 day
Truck	1.6 € per km	90 €	50 km

While some studies claim that autonomous barges may be faster and cheaper than traditional barges (see e.g. [11] [12]), it is beyond the scope of this paper to justify any such claims. Arguments can be made in favour of decreased chartering prices due to lower manning requirements or in favour of increased chartering prices due to the more expensive assets. Thus, for the purposes of this study, the application of autonomy merely entails prolonging the available hours of operation per day to continuous operation while maintaining the same chartering price.

2.3 Port Characteristics

The study revolves around two prospective inland terminals based on the blueprints of the DFDS terminals in Rotterdam and Ghent. Although not inland terminals per se, for the purposes of this study, the terminals are modelled after the XL terminal model presented by M. Smid, S. Dekker and B. Wiegmans [23] in terms of the size and terminal equipment in order to calculate loading/unloading capacities of the two terminals and consequently the economic feasibility of the solution within its business ecosystem. These characteristics are shown in Table 4. To calculate the competing scenarios of the solutions, the study uses port tariffs from Port of Rotterdam and North Sea Port, as shown in Table 5, and terminal service fees from DFDS and C.Ro in Rotterdam and Ghent, as shown in Table 6. This allows for a computation of scenarios that are in line with existing terms of business and operations. Do note that while terminal storage can be

Journal of Physics: Conference Series **2867** (2024) 012030 doi:10.1088/1742-6596/2867/1/012030

costly, any storage above 72 hours is free of charge at the terminals in question, and thus it has not been included in the calculations of this study.

Table 4. Terminal sizes used in this study

Type	Volume/year (TEU)	Area size (ha)	Quay length	Harbor Cranes	Reach Stackers	Terminal Tractors [a]
Terminal	200,000	20	300	2	3	3

[a] The number of terminal tractors is set to the same as reach stackers for fair comparison between solutions.

Table 5. Port services efficiencies and fees used in this study.

Service	Rotterdam (€)	Ghent (€)
Port tariffs per GT [34] [31]	0.10	0.05
Fairway charges	0.00	0.00
Lock charges	0.00	0.00
Pilotage	0.00	0.00

Table 6. Terminal services efficiencies and fees used in this study.

Service	Moves per hour (#)	Price per move (€)
Reach stacker, lift	15	30.00
Harbour crane, lift	25	45.00
Terminal tractor, pull	12	25.00
Terminal gate, in/out	N/A	11.50
Cross-dock	N/A	172.00

2.4 Cargo characteristics

To investigate the economic and environment viability of green, autonomous ships in realistic scenarios, the study inspected cargo flows between the relevant regions at NUTS2[1] level to evaluate the potential for converting goods from road to water. The Eurostat dataset for 2022 include more than 235.000 lines of data and details departures and destinations (NUTS2), goods types (NST2007), tonnage, frequency, and transported kilometres. While specific addresses are not provided in the dataset, it still provides sufficient granularity to inspect potential cargo flows and conversions for the purposes of the economic analyses of this study. Figure 3 shows the NUTS2 regions of interest for Netherlands (left) and Belgium (right).

Acknowledging that not all goods are suitable for inland shipping, e.g. time-sensitive or high-value items, irrelevant goods types were filtered out to investigate the volumes of only those realistically convertible [29] (see Appendix A). To align the study with the ambitions of the

[1] NUTS2 refers to the Nomenclature of Territorial Units for Statistics at granularity level 2 [35]

European Green Deal, 25%, 50% and 100% conversion scenarios of relevant goods types were created [30], as shown in in Table 7. This study does not target specific goods types outside of the time-value filtering, although some types may be more interesting than others (see Appendix B).

Figure 3 NUTS 2 levels of interest. Green indicates Rotterdam and red indicates Ghent

Table 7. Conversion potential between Rotterdam and Ghent per week.

Corridor	25% conversion [a]	50% conversion [a]	100% conversion
Rotterdam – Ghent	264.35 units	528.70 units	1057.39 units
Ghent – Rotterdam	291.86 units	583.71 units	1167.42 units

[a] Based on European Green Deal ambitions [30].

Aggregated on the volumes between the regions, it is determined that the average weight of the cargo transported on road is 15.46 tonnes per trailer. This number have been used to determine cargo tariffs in ports, the port equipment needed as well as the total weight of the barge and therewith the consumptions and emissions.

2.5 Emissions characteristics

The study applies aggregated emissions data for the transport equipment to offer an overview of environmental implications of the solutions, as shown in Table 8, based on a combination of international frameworks and previous research (see e.g. [24] [25] [26] [27] [28]) as well as interviews with logistics firms and extrapolation from data within these three. For the purpose of this study, the average travel distance for reach stackers and terminal tractors is set to 250 metres as measured on terminal layouts, resulting in 500 metres per move with no dual cycling in place.

Table 8. Emissions data for diesel equipment for the purposes of this study.

Equipment	Consumption (diesel)	Emissions [a] (diesel)	Consumption (electric)	Emissions [b] (electric)
Barge	0.0065 l/t-km	0.0161 kg CO2/t-km	40.00 kWh/km	9.3200 kg CO2/km
Truck	0.038 l/t-k,	0.1000 kg CO2/t-km	1.80 kWh/km	0.4194 kg CO2/km
Harbour crane	2.77 l/move	7.5547 kg CO2/move	4.00 kWh/move	0.9320 kg CO2/km
Reach stacker	5.00 l/km	4.2350 kg CO2/km	2.24 kWh/km	0.5219 kg CO2/km
Terminal tractor	3.24 l/km	2.7358 kg CO2/km	1.44 kWh/km	0.3355 kg CO2/km

[a] Based on a diesel fuel with energy density of 0.847 kg/l and CO2 emission of 3.22 kg CO2 per kg [32].
[b] Based on a blended grid intensity of 0.233 kg CO2/kWh between Netherlands and in Belgium [33].

3 Economic and environmental viability

Computing the methodology as described above, one finds an array of valuable insights pertaining to the transport times, transits, prices and emissions of the solutions.

Regarding the time calculations, as shown in Table 9, the truck solution is a significantly faster transport option, which is in line with the notion of time-value criticalities, as mentioned [29]. Moreover, the RoRo solution is faster than the LoLo solution from a holistic view, given that while the barge transport times are identical, the transshipment times for the RoRo solution are significantly below that of the LoLo solution. This is because the barge itself is faster to unload with terminal tractors as opposed to a harbor crane while the RoRo solution also does not require transshipment from the terminal to the truck. This is important, as it may also enable RoRo shipping solutions to terminals with no to little infrastructural equipment (e.g., quays in city centers). It is important to note that the study does not consider the autonomous barge to be neither faster nor slower than traditional barges, making the findings applicable to both.

Table 9. Time calculations for barge

Parameter	RoRo solution	LoLo solution	Truck solution
Time for transport	11.64 h	11.64 h	1.88 h
Time for transhipment: barge <> terminal	3.83 h	7.04 h	0.00 h
Time for transhipment: terminal <> truck	0.00 h	7.82 h	0.00 h
Time for last mile (hours)	0.63 h	0.63 h	0.63 h
Total time door-to-door (hours)	16.10 h	27.13 h	2.50 h

Regarding the operational implication of the process times, as shown in Table 10, the faster transhipment times for the RoRo solution means that while the LoLo solution in this study carries 2.5 times as much cargo per voyage as the RoRo, the solution will not have shipped 2.5 times as much cargo over the course of a week given that the RoRo solution can undertake more transits per week under a fixed liner-setup. Still, the truck will be able to outperform both on speed. Applying autonomy extends the operational range significantly for all solutions.

Table 10. Transit calculations for barges

Parameter	RoRo solution	LoLo solution	Truck solution
Voyages transits per day (normal)	1.16	0.96	5.33
Voyages transits per day (autonomous)	1.55	1.28	12.80
Last mile transits per day (normal)	16.00	16.00	N/A

Regarding the economic consequences of the operational implications, as shown in Table 11, the increased transits per day for the RoRo solution provides a subsequent lower transit price compared to the LoLo solution both under normal and autonomous operation, with the latter further decreasing the price due to the continuous operation setup. Using the weights as defined in the methodology, precise port and terminal fees has been calculated per cargo unit, including also the fee for last mile transit. Noticeably, the terminal handling costs of the RoRo solution is around half that of the LoLo solution given the cheaper costs of using terminal tractors over harbor cranes, and the lack of transshipment from terminal to truck. However, the transit fees and port fees are cheaper for the LoLo solution given that the fees related to the barge itself will be split amongst a greater number of cargo units onboard, making these fees cheaper per cargo unit. While a theoretically precise comparison would further imply the cross-docking of containers for last mile transportation in the LoLo solution, this variable has been omitted in this study, as it would distort the comparison of potential solutions. The truck solution, in comparison, carries precisely one cargo unit per transit, providing a concrete price per unit.

Table 11. Total fees for each transport solution

Parameter	RoRo solution	LoLo solution	Truck solution
Total vessel fee per transit – normal	4297.96 €	5188.70 €	320.00 €
Total vessel fee per transit – autonomous	3223.47 €	3891.52 €	320.00 €
Total port fee for barge per transit	783.05 €	783.05 €	0.00 €
Total port fee for cargo per unit	2.37 €	1.71 €	0.00 €
Total terminal fee for cargo per unit	73.00 €	143.00 €	0.00 €
Total last mile fee per transit	90.00 €	90.00 €	0.00 €

As barges may not be fully utilised for each trip, various utilisation rates have been applied to see fluctuations in price as shown in Table 12 and 13 for diesel & traditional, and electric & autonomous setups respectively. This also provides the opportunity to calculate exact prices for each unit under the different solutions. Utilisation rates does not apply to trucks, as it is assumed that a truck carries precisely one unit, i.e. 100%, or nothing at all. The findings indicate that the RoRo solution is cheapest under all utilisation rates, while the truck solution is always the most expensive option. Comparing this to the emissions per unit, it is also seen that the total emission per unit using a waterborne solution is better than the truck alternative under all utilisation scenarios, with LoLo being the greenest throughout them all.

When applying electrification and autonomy, the price decreases for all modes except the truck under all utilisation scenarios (given its distance-based chartering setup, as mentioned). In terms of emissions, the LoLo solution remains the greenest solution, with emissions less than 50% of the RoRo solution and 25% of the truck solution. Likewise, the RoRo solution will be almost 50% greener than the truck solution. This means that the AEGIS electric, autonomous RoRo barge concept of 69 trailers is a viable alternative to truck transport both from an economic and environmental perspective – as would also be an electric, autonomous Sendo Liner XL barge if cross-docking is omitted from the calculations and/or the broader need for containerization of roadborne goods is otherwise overlooked.

Table 12. Prices and emissions under different utilisation scenarios (diesel & traditional).

Utilisation rate	RoRo solution		LoLo solution		Truck solution	
	Price (€)	CO2e (kg)	Price (€)	CO2e (kg)	Price (€)	CO2e (kg)
100% utilisation	239.00	439,29	269.30	338,20	320,00	829,20
80% utilisation	257.41	487,06	277.78	356,93	320,00	829,20
60% utilisation	288.10	566,67	291.92	388,14	320,00	829,20

Table 13. Prices and emissions under different utilisation scenarios (electric & autonomous)

Utilisation rate	RoRo solution Price (€)	RoRo solution CO2e (kg)	LoLo solution Price (€)	LoLo solution CO2e (kg)	Truck solution Price (€)	Truck solution CO2e (kg)
100% utilisation	223.43 €	21.95 kg	261.93 €	10.60 kg	320,00 €	62.91 kg
80% utilisation	237.95 €	27.35 kg	268.57 €	12.72 kg	320,00 €	62.91 kg
60% utilisation	262.14 €	36.35 kg	279.63 €	16.25 kg	320,00 €	62.91 kg

4. Ecosystem implications

As mentioned, for a potential ship service to be attractive in the long term and thus actually implemented, it is presupposed that the relevant logistics actors in the ecosystem would need an acceptable financial, environmental and/or operational benefit of the new transport setup, striking a balance where all participants benefit from their involvement. Consequently, the implications of the three solutions across the business ecosystem they inhabit have been calculated and displayed in Table 14 and Table 15, with red indicating negative numbers.

Table 14. Ecosystemic implications of present transport solutions (**diesel & traditional**).

	RoRo solution Price (€)	RoRo solution CO2e (kg)	LoLo solution Price (€)	LoLo solution CO2e (kg)	Truck solution Price (€)	Truck solution CO2e (kg)
Cargo owner(s)	-142,864.03	-215,993.22	-154,167.00	-135,438.88	-177,600.00	-719,715.56
Barge operator(s)	43,213.15	-170,028.90	20,452.60	-81,431.99	0.00	0.00
Port A	6,123.92	0.00	2,932.93	0.00	0.00	0.00
Terminal A	20,568.00	-759.18	40,398.00	-4,192.86	0.00	0.00
Port B	3,061.96	0.00	1,466.47	0.00	0.00	0.00
Terminal B	19,947.00	-759.18	38,967.00	-5,368.07	0.00	0.00
Truck operator(s)	49,950.00	-44,445.95	49,950.00	-44,445.95	177,600.00	-719,715.56

Scenario: Rotterdam – Ghent roundtrip, 25% freight conversion (uneven flow), 80% barge utilisation.

Table 15. Ecosystemic implications of present transport solutions (**electric & autonomous**).

	RoRo solution Price (€)	RoRo solution CO2e (kg)	LoLo solution Price (€)	LoLo solution CO2e (kg)	Truck solution Price (€)	Truck solution CO2e (kg)
Cargo owner(s)	-132,060.74	-26,817.61	-149,053.85	-18,695.66	-177,600.00	-46,553.40
Barge operator(s)	32,409.86	-14,993.04	15,339.45	-5,877.95	0.00	0.00
Port A	6,123.92	0.00	2,932.93	0.00	0.00	0.00
Terminal A	20,568.00	-93.11	40,398.00	-517.26	0.00	0.00
Port B	3,061.96	0.00	1,466.47	0.00	0.00	0.00
Terminal B	19,947.00	-93.11	38,967.00	-662.09	0.00	0.00
Truck operator(s)	49,950.00	-11,638.35	49,950.00	-11,638.35	177,600.00	-46,553.40

Scenario: Rotterdam – Ghent roundtrip, 25% freight conversion (uneven flow), 80% barge utilisation.

Converting 25% of the cargo flowing between the NUTS2 regions of Rotterdam and Ghent, with 264 units and 291 units transported southbound and northbound respectively, it can be seen that the RoRo solution offers the greatest price advantage. From an ecosystem perspective, all maritime stakeholders such as barge operator(s), ports and terminals will benefit from the transition towards any of the waterborne transport modes. Also, for the cargo owner(s), both the RoRo and the LoLo solutions become economically viable when compared to trucking even in the traditional setup with diesel-fuelled, manned barges (provided that the customer does not require cross-dock). The same can be seen for the emissions associated with the transport modes, with LoLo and RoRo solutions emitting around only 20% and 30% that of the truck solution. Seeing the cargo owner(s) emissions as the total emissions of the transport solution, all actors in the ecosystem should also be interested in making the shift when looking exclusively on the emissions associated with the service(s). At the same time, some may argue that truck operators are not interested in the shift to waterborne transport modes, while other argue that they will be due to the more profit-effective use of their assets that the waterborne solution provides. Regardless, this shows that already existing waterborne transport forms can provide significant economic and environmental benefits to the actors in the ecosystem already today, provided that the actors in the chain can allow for longer transport times.

For a future scenario with barges and trucks that are electric and autonomous, the latter would entail further cost savings per week for the cargo owner of around 8% for RoRo and 3% for LoLo while the former would reduce the emissions down to 12% for RoRo and 14% for LoLo compared to their diesel counterparts and 58% for RoRo and 40% for LoLo compared to the electric truck solution. Said differently, making the vessels electric and autonomous only exacerbates the benefits already latent in the waterborne transport modes today, with RoRo the price-effective solution and LoLo the emission-effective solution. Regardless, it seems both waterborne solutions provide both economic and environmental benefits to the ecosystem actors. At the same time, it also becomes apparent that some actors may prefer one waterborne solution over another, with terminals pulling towards LoLo solutions while ports and barges pull towards RoRo solutions due to the current business model setup.

5. Conclusion

The paper sat out to study the economic and environmental viability of green, autonomous ships on the inland waterways as an alternative to the predominant truck transportation of today by first exploring the viability of already existing vessels to create the baseline from which the potential implications brought about by electrification and autonomy could be investigated. A holistic approach using the concept of business ecosystem was taken to both traditional and autonomous ship feasibility by investigating the economic and environmental viability in the broader logistics ecosystem that is inhabited. Data was collected on an array of variables to create a full view of a hinterland supply chain using both large statistical datasets, publicly available information and in-depth interviews with logistics companies, ports and terminal operators.

The study finds that even without the introduction of electrification and autonomy, all maritime stakeholders will benefit from transitioning towards a waterborne transport mode, with RoRo the more price-effective solution and LoLo the more emission-effective solution. This shows that existing transport forms on the inland waterways can provide significant economic and environmental benefits to the actors in the ecosystem already today, provided that the actors can allow for longer transportation times and cargo bundling. This goes against some preconceived discourses around the use of barges in general and RoRo barges in particular and is an important finding in its own right. For future electric and autonomous barges, the benefits only become greater.. While arguments are plentiful as to the potential decrease in operational expenses from the introduction of autonomy, this study does not assume any such decreases. Future studies should apply various cost variables and scenarios from autonomy to this case study to see additional potentials for economic and environmental attractiveness of the solution(s). Such autonomy would concern both the transport equipment and the terminal equipment.

Concludingly, the study proves that ecosystem analysis is a viable framework to investigate the holistic implications of green, autonomous shipping in realistic transport scenarios. While the study departs from the traditional business model constellations present in the industry today, future studies should explore how ecosystem thinking may enable entirely new models for collaboration and commercialisation between the stakeholders in the ecosystems. For instance, although the new electric and autonomous concepts save both on costs and on emissions for almost all ecosystem actors when compared with traditional barge concepts, individual actors may prefer one type of waterborne solution over the other if maximising for their own individual benefits under linear business models. Future studies on business model innovation for business ecosystems in general and autonomous shipping in particular should investigate how to reconcile these potentially opposing forces when introducing new, radical technologies through the use of innovative business model constellations. Additionally, understanding the specific capital expenses associated with introducing autonomous ships in their logistics ecosystems should be investigated to understand the barriers to entry and financial risks required to leverage the cost and emissions benefits of the innovation, as found in this study, and illuminate how innovative business and investment models can be applied to derisk and capitalise on the transformation.

6. Acknowledgements

This paper has been completed in extension of the research conducted within the AEGIS project (Advanced, Efficient and Green Intermodal Systems) under the framework of the European Union Horizon Europe Programme Grant Agreement No. 859992.

7. References

[1] United Nations, “Sustainable Transport,” Sustainable Development, United Nations, [Online]. Available: https://sustainabledevelopment.un.org/topics/sustainabletransport#:~:text=Target%2011.2%20aims%20by%202030,with%20disabilities%20and%20older%20persons. [Accessed 24 05 2024].

[2] European Commission, “Make Transport Greener - EU Green Deal Transport Factsheet,” European Commission, Brussels, 2021.

[3] S. Greene and A. Lewis, “Global Logistics Emissions Council Framework for Logistics Emissions Accounting and Reporting,” Global Logistics Emissions Council, 2019.

[4] H. v. Essen, D. Fiorello, K. E. Beyrouty, C. Bieler, L. v. Wijngaarden, A. Schroten, R. Parolin, M. Brambilla, D. Sutter, S. Maffii and F. Fermi, “Handbook on the External Costs of Transport,” Publications Office for the European Union, Brussels, 2020.

[5] Eurostat, “Freight transport statistics - modal split. Eurostat Statistics Explained.,” 2023. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Freight_transport_statistics_-_modal_split.

[6] ITF, “The Impact of Mega-Ships: Case-Specific Policy Analysis,” OECD, Paris, 2015.

[7] F. ". J. Camacho, “Ship that destroyed the Baltimore bridge was big. It wasn’t the biggest.,” E&E News by Politico, 27 03 2024.

[8] V. Yee and J. Glanz, “How One of the World’s Biggest Ships Jammed the Suez Canal,” The New York Times, 17 07 2021.

[9] E. Lindstad, G. S. Eskeland, I. Sandaas and S. Steen, “Revitalization of short sea shipping through slender, simplified and standardized designs,” Soc. Nav. Archit. Mar. Eng. SNAME Trans., pp. 109-123, 2016.

[10] Ø. J. Rødseth, D. A. Nesheim, A. Rialland and E. A. Holte, "The Societal Impacts of Autonomous Ships: The Norwegian Perspective," pp. 357-376, 2023.
[11] E. Ziajka-Poznańska and J. Montewka, "Costs and Benefits of Autonomous Shipping - A Literature Review.," Applied Sciences, vol. 11, no. 10, 2021.
[12] A. Tsvetkova and M. Hellström, "Creating value through autonomous shipping: An ecosystem perspective.," Maritime Economics & Logistics, vol. 24, no. 2, p. 255–277, 2022.
[13] H. Ghaderi, "Wider implications of autonomous vessels for the maritime industry: Mapping the unprecedented challenges.," Advances in Transport Policy and Planning,, vol. 5, p. 263–289, 2020.
[14] A. Akbar, A. K. A. Aasen, M. K. Msakni, K. Fagerholt, E. Lindstad and F. Meisel, "An economic analysis of introducing autonomous ships in a short-sea liner shipping network," International Transactions in Operational Research., vol. 28, no. 4, pp. 1740-1764, 2020.
[15] G. T. H. Nguyen, D. Ruzaeva, J. C. Góez and M. Guajardo, "Insights on the introduction of autonomous vessels to liner shipping networks," Journal of Shipping and Trade, vol. 7, p. 12, 2022.
[16] J. L. Dantas and G. Theotokatos, "A framework for the economic-environmental feasibility assessment of short-sea shipping autonomous vessels," Ocean Engineering, vol. 279, 2023.
[17] R. Adner, The Wide Lens: What Successful Innovators See That Others Miss, Penguin Books, 2013.
[18] De Vlaamse Waterweg; Wallonie Mobilite SPW, "Voies Navigables de France, Societe du Canal Seine-Nord Europe," Seine-Scheldt, [Online]. Available: https://seine-scheldt.eu/homepage/. [Accessed 05 03 2024].
[19] EuRIS, "EuRIS Portal," [Online]. Available: https://www.eurisportal.eu.
[20] Eurostat, "Unitisation of goods in the EU is growing," Freight transported in containers - statistics on unitisation, 2024.
[21] Sendo Shipping, "Sendo Liner: Innovation is our course," Sendo Shipping, [Online]. Available: https://sendo-shipping.nl/sendo-liner/. [Accessed 23 05 2024].
[22] AEGIS, "AEGIS Autonomous Ship," SINTEF Ocean, [Online]. Available: https://aegis.autonomous-ship.org/. [Accessed 23 05 2024].
[23] M. Smid, S. Dekker and B. Wiegmans, "Modeling the cost sensitivity of intermodal inland waterway terminals: A scenario based approach," Transportation Research Part A, vol. 85, pp. 112-122, 2016.
[24] G. Wilmsmeier and T. Spengler, "Energy Consumption and Energy Efficiency Indicators in Container Terminals - A National Inventory," in IAME 2016, Hamburg, 2016.
[25] J. v. Duin and H. Geerlings, "Estimating CO2 Footprints of Container Terminal Port Operations," International Journal of Sustainable Development and Planning, vol. 6, no. 4, p. 459–473, 2011.
[26] W. Shoman, S. Yeh, F. Sprei, P. Plötz and D. Speth, "Battery electric long-haul trucks in Europe: Public charging, energy, and power requirements," Transportation Research Part D, vol. 121, 2023.
[27] D. Hall and N. Lutsey, "Estimating the infrastructure needs and costs for the launch of zero-emission trucks | International Council on Clean Transportation," The International Council on Clean Transportation (ICCT), Washington, 2019.
[28] B. Al-Hanahi, I. Ahmad, D. Habibi and M. A. S. Masoum, "Charging Infrastructure for Commercial Electric Vehicles: Challenges and Future Works," IEEE Access, vol. 9, pp. 121476-121492, 2021.
[29] ASEK Group, "Analysmetod och samhällsekonomiska - ASEK 8.0," Swedish Road Authority (Trafikverket), 2024.
[30] European Commission, "Inland waterway transport - NAIADES III action plan 2021-2027," European Commission, [Online]. Available: https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12789-Inland-waterway-transport-NAIADES-III-action-plan-2021-2027_en.
[31] North Sea Port, "Regulations Tariffs/Fees 2024," North Sea Port, Flanders, 2024.
[32] Smart Freight Centre, "Global Logistics Emissions Council Framework V3.0," 2024.
[33] European Environment Agency, "Greenhouse gas emission intensity of electricity generation in Europe," European Environment Agency, 2023 10 24. [Online]. Available: https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emission-intensity-of-1. [Accessed 23 05 2024].
[34] Port of Rotterdam, "General Terms and Conditions Including Port Tariffs," Port of Rotterdam, Rotterdam, 2023.
[35] Eurostat, "NUTS - NOMENCLATURE OF TERRITORIAL UNITS FOR STATISTICS," European Commission, [Online]. Available: https://ec.europa.eu/eurostat/web/nuts.

Journal of Physics: Conference Series **2867** (2024) 012030 doi:10.1088/1742-6596/2867/1/012030

Appendix A – Time-value Goods

Code + Description (NST2007 + AMSGODS)	Time-value (average)	Conversion characteristics
1. Products of agriculture, hunting, and forestry; fish and other fishing products	0.61	Low time-value. 25-50% conversion scenario.
2. Coal and lignite; crude petroleum and natural gas	0.56	Low time-value. 25-50% conversion scenario..
3. Metal ores and other mining and quarrying products; peat; uranium and thorium	0.15	Low time-value. 25-50% conversion scenario.
4. Food products, beverages, and tobacco	2.85	Medium time-value. 25-50% conversion scenario.
5. Textiles and textile products; leather and leather products	23.56	High time-value. 0% conversion scenario.
6. Wood and products of wood and cork (except furniture); articles of straw and plaiting materials; pulp, paper and paper products; printed matter and recorded media	0.88	Low time-value 25-50% conversion scenario.
7. Coke and refined petroleum products	0.79	Low time-value. 25-50% conversion scenario.
8. Chemicals, chemical products, and man-made fibres; rubber and plastic products; nuclear fuel	2.89	Medium time-value 25-50% conversion scenario.
9. Other non-metallic mineral products	0.73	Low time-value 25-50% conversion scenario.
10. Basic metals; fabricated metal products, except machinery and equipment	2.82	Medium time-value 25-50% conversion scenario.
11. Machinery and equipment not elsewhere classified; office machinery and computers; electrical machinery and apparatus not elsewhere classified; radio, television and communication equipment and apparatus; medical, precision and optical instruments; watches and clocks	27.03	High time-value. 0% conversion scenario.
12. Transport equipment	13.75	High time-value. 0% conversion scenario.
13. Furniture; other manufactured goods not elsewhere classified	5.71	Medium time-value. 25-50% conversion scenario.
14. Secondary raw materials; municipal wastes and other wastes	0.44	Low time-value. 25-50% conversion scenario.
15. Mail, parcels	0.11	Low time-value. 25-50% conversion scenario.
16. Equipment and material utilised in the transport of goods	N/A	Assumed low time-value. 25-50% conversion scenario.
17. Goods moved in the course of household and office removals; baggage and articles accompanying travellers; motor vehicles being moved for repair; other non-market goods not elsewhere classified	N/A	Assumed high time-value and therefore not included.
18. Grouped goods: a mixture of types of goods which are transported together	N/A	Assumed Low/Medium time-value. 25-50% conversion scenario.
19. Unidentifiable goods: goods which for any reason cannot be identified and therefore cannot be assigned to groups 01-16.	N/A	Unknown and therefore not included.
20. Other goods not elsewhere classified	N/A	Unknown and therefore not included.
99. Grouped goods due to confidentiality and quality	N/A	Assumed high time-value and therefore not included.

Appendix B – Freight potential Rotterdam – Ghent

Load Region	Unload Region	Goods Type	Tonnes (year)	Kilometres (year)	Movements (year)	Conversion Rate (Low)	Conversion Rate (High)	Conversion Rate (full)	Movements (week, low)	Movements (week, high)	Movements (week, full)
NL330	BE230	18	163035.62	3654625.43	11379.72	25%	50%	100%	54.71	109.42	218.84
NL330	BE230	04	198774.27	4308484.02	11337.27	25%	50%	100%	54.51	109.01	218.02
NL330	BE230	16	34359.64	754189.50	6469.26	25%	50%	100%	31.10	62.20	124.41
NL330	BE230	01	92810.27	2043238.50	5564.03	25%	50%	100%	26.75	53.50	107.00
NL330	BE230	08	93398.30	1119017.05	5368.08	25%	50%	100%	25.81	51.62	103.23
NL330	BE230	09	58536.19	932968.93	3409.18	25%	50%	100%	16.39	32.78	65.56
NL330	BE230	06	39116.17	848168.19	2893.38	25%	50%	100%	13.91	27.82	55.64
NL330	BE230	10	36020.88	873891.82	2498.60	25%	50%	100%	12.01	24.03	48.05
NL330	BE230	03	59745.69	317163.51	2498.51	25%	50%	100%	12.01	24.02	48.05
NL330	BE230	14	25991.57	505480.08	1443.82	25%	50%	100%	6.94	13.88	27.77
NL330	BE230	13	7322.26	621020.50	1003.73	25%	50%	100%	4.83	9.65	19.30
NL330	BE230	15	9263.91	959646.44	711.05	25%	50%	100%	3.42	6.84	13.67
NL330	BE230	07	5729.46	81345.92	402.84	25%	50%	100%	1.94	3.87	7.75
NL330	BE230	17	15.21	1590.98	4.93	25%	50%	100%	0.02	0.05	0.09
NL330	BE230	02	0.00	0.00	0.00	25%	50%	100%	0.00	0.00	0.00
NL330	BE230	05	3898.69	143489.33	369.36	0%	0%	0%	0.00	0.00	0.00
NL330	BE230	11	31477.48	1467399.37	2303.84	0%	0%	0%	0.00	0.00	0.00
NL330	BE230	12	26130.47	743985.62	1687.89	0%	0%	0%	0.00	0.00	0.00
NL330	BE230	19	10890.99	135581.47	624.62	0%	0%	0%	0.00	0.00	0.00
NL330	BE230	20	11345.63	97211.27	602.76	0%	0%	0%	0.00	0.00	0.00
NL330	BE230	99	4747.42	759.59	190.00	0%	0%	0%	0.00	0.00	0.00
Total per week			**912610.12**	**377101.11**	**60762.88**				**264.35**	**528.70**	**1057.39**

Load Region	Unload Region	Goods Type	Tonnes (year)	Kilometres (year)	Movements (year)	Conversion Rate (Low)	Conversion Rate (High)	Conversion Rate (full)	Movements (week, low)	Movements (week, high)	Movements (week, full)
BE230	NL330	16	77359.50	1729384.59	15636.08	25%	50%	100%	75.17	150.35	300.69
BE230	NL330	04	223108.27	2009138.48	9976.89	25%	50%	100%	47.97	95.93	191.86
BE230	NL330	18	126918.85	1391146.17	7633.21	25%	50%	100%	36.70	73.40	146.79
BE230	NL330	08	127902.69	763409.26	5559.40	25%	50%	100%	26.73	53.46	106.91
BE230	NL330	01	110262.11	858725.05	4961.67	25%	50%	100%	23.85	47.71	95.42
BE230	NL330	09	105330.05	752931.55	4496.84	25%	50%	100%	21.62	43.24	86.48
BE230	NL330	10	85177.28	1584966.75	4225.82	25%	50%	100%	20.32	40.63	81.27
BE230	NL330	06	74205.05	662300.50	3594.31	25%	50%	100%	17.28	34.56	69.12
BE230	NL330	03	51377.10	272417.87	1648.90	25%	50%	100%	7.93	15.85	31.71
BE230	NL330	14	31667.23	244229.40	1513.52	25%	50%	100%	7.28	14.55	29.11
BE230	NL330	13	8785.55	253807.59	603.63	25%	50%	100%	2.90	5.80	11.61
BE230	NL330	07	12548.13	112306.09	571.60	25%	50%	100%	2.75	5.50	10.99
BE230	NL330	15	3199.13	29463.32	213.77	25%	50%	100%	1.03	2.06	4.11
BE230	NL330	02	1775.73	25519.21	70.40	25%	50%	100%	0.34	0.68	1.35
BE230	NL330	05	8628.38	416571.47	1288.45	0%	0%	0%	0.00	0.00	0.00
BE230	NL330	11	30473.93	307019.31	1968.70	0%	0%	0%	0.00	0.00	0.00
BE230	NL330	12	17904.63	239001.15	1208.28	0%	0%	0%	0.00	0.00	0.00
BE230	NL330	17	0.00	0.00	0.00	25%	50%	100%	0.00	0.00	0.00
BE230	NL330	19	20268.26	229406.90	1050.52	0%	0%	0%	0.00	0.00	0.00
BE230	NL330	20	7122.32	70557.57	403.48	0%	0%	0%	0.00	0.00	0.00
BE230	NL330	99	838.47	10604.76	52.65	0%	0%	0%	0.00	0.00	0.00
Total per week			**1124852.69**	**230055.90**	**66678.12**				**291.86**	**583.71**	**1167.42**