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A review of the state-of-the-art Sustainable and Climate-resilient inland waterway vessels

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ABSTRACT

Inland water vessels are impacted by climate change in two respects. First of all, they will need to convert to low-impact power propulsion and energy (PPE) systems. Secondly, they will need to deal with the impact of climate change, especially longer periods of very low and high water. This paper reviews the multi facet impacts of climate change on inland waterway vessel performance and problems associated with the choice of alternative power energy and propulsion (PPE) system on the vessel's performance

KEY WORDS

climate-change, decarbonisation, inland waterway vessels, shallow-water

INTRODUCTION

Inland waterways play an important role in transportation, presenting a sustainable and energy-efficient means with better environmental performance than other transport modes in terms of CO_2 emissions by transport work (gCO_2e/tkm) (Doll et al., 2020). In the Netherlands, inland waterway transport accounts for approximately 41 % of the total freight transport among the main hinterland transport modalities according to ("Eurostat", 2023), contributing to the decongestion of road and rail networks (Vinke et al., 2022), and presents an economically competitive alternative in terms of cost and tonnage. Inland waterway vessels are affected by climate change in dual dimensions. First, there is an ambition to mitigate climate change by abating greenhouse gas (GHG) emissions, which, according to the European Environmental Agency (Doll et al., 2020), as of 2018, inland water transport emits 33 gCO_2/tkm, making up a share of about 17 % of CO_2 emissions from the transport sector. However, these vessels need to adapt to the predominant effects of climate change on waterways, ensuring sufficient cargo transport and navigation during prolonged periods of severe drought and flood, resulting in high and low water levels. To achieve a significant emission reduction, the use of low-impact energy carriers complemented by suitable energy converters is required (Zwaginga & Pruyn, 2022), and the adoption of alternative energy carriers poses inherent challenges owing to their lower energy densities. Meeting propulsion and power energy demands necessitate additional space and weight for storage, directly affecting vessel performance (Wang & Wright, 2021). In addition, the adverse effects of climate change influence vessel performance (Jonkeren et al., 2013).

Inland waterway vessels differ significantly from ocean-going vessels; given that they are much smaller in size and the environment in which they operate. Inland waterway vessels are designed to navigate and manoeuvre through confined and restricted waterways such as rivers with bridges and locks (Radojčić et al., 2021). Although ocean-going vessels sail under adverse weather conditions, they do not have the limitations of inland water vessels. The physical interaction between the hull and waterway, and thus the flow around the hull, influences the hull form design and maximum dimensions of inland

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water vessels to suit the respective waterway classifications in which they operate (Zeng, 2019). The length is restricted by the lock length, the breadth is restricted by the lock width, the air draught (vessel height above the water line) is limited by the bridge vertical clearance, and the vessel draught is limited by the water depth (Guesnet et al., 2014). These distinguish inland waterway vessels from ocean-going vessels, which underpins the fact that their efficient operations are affected more by the effects of climate change. When this is not addressed, inland water transport would become a less reliable transport mode and could lead to a modal shift that is undesirable because the other transport modes do not have the capacity to compensate for the loss of capacity by inland water transport (IWT) (Vinke et al., 2022), whereas IWT has underexploited reserves. This would lead to a disruption of the supply chain, as well as an increase in environmental pollution from road transport. A fundamental element for ensuring the effective and safe transport of cargo along these routes involves a comprehensive understanding of ship hydrodynamics (Gebraad et al., 2021), actions required to adapt fleets, ensuring transportation reliability (Kempmann et al., 2023), and reducing the environmental footprint. The challenge however faced by ship designers and naval architects is finding the ”sweet spot”, an ideal balance between achieving zero-emission, adapting to climate change and vessel performance; thus, the trade-offs between adapting short-term measures and flexibility to meet uncertain future requirements are imperative, and hence careful consideration from the design point of view (Andrews & Erikstad, 2015).

This literature review focuses on current state-of-the-art research on the decarbonisation of inland water transportation and adaptation of inland water transport to climate change. The main research question for this literature review is:

“What is the current state of climate-resilient and sustainable inland water vessel design?”

The rest of this paper is structured as follows. In the next section, the Methodology is outlined, providing insight into the literature exploration approach. Following this, Results and Discussions presents and discusses the outcomes derived from the reviewed literature. Finally, in Conclusion and Future Study, a concise summary of the entire paper is provided, encapsulating the essential findings from the literature outcomes and the author’s reflection on future research directions from identified gaps.

METHODOLOGY

To comprehensively organise and evaluate findings from past research, we conducted a methodological exploration of the literature utilising specific search terms to answer the main research question highlighted in the previous section. The search strategy for this study stems from two concepts derived from the main research question: one concerns the climate change adaptation of inland waterway vessels and the decarbonisation of inland waterway vessels. For the first concept, the search terms included “climate change” OR “low water” OR “shallow water” AND “inland navigation” OR “IWT” OR “inland water*”. Whereas for the second concept, the search terms included “sustainability” OR “decarbonisation” OR “emission reduction” OR “GHG emissions” AND “inland navigation” OR “IWT” OR “inland water*”. The snowball technique was also used in the literature search, involving the examination and assessment of references cited in the selected primary literature for relevance and potential inclusion in this study. The initial search for resources was conducted using databases connected to the TU Delft library, as summarised in Table 1. The articles selected for this literature review provide a background to answer the research questions. Selection and exclusion were performed first by scanning the titles and keywords, after which a detailed perusal of the abstracts, introductions, and conclusions of articles was performed to assess their relevance for this work.

Table 1: Search resources and types of documents

Information resources or database for preliminary search	**Types of documents**
Web of Science, Google Scholar, and TU Delft repository	Journal articles, conference papers, books
Secondary resources	**Types of documents**
Cited references of primary resources	Journal articles, conference papers

RESULTS AND DISCUSSIONS

The search terms led to a selection of 392 papers, and after reviewing the titles, approximately 150 remained. Based on their abstracts, a further 65 were dismissed, as these primarily addressed logistics, policy management, or hydrology. The state-of-the-art review began by exploring the remaining 51 papers.

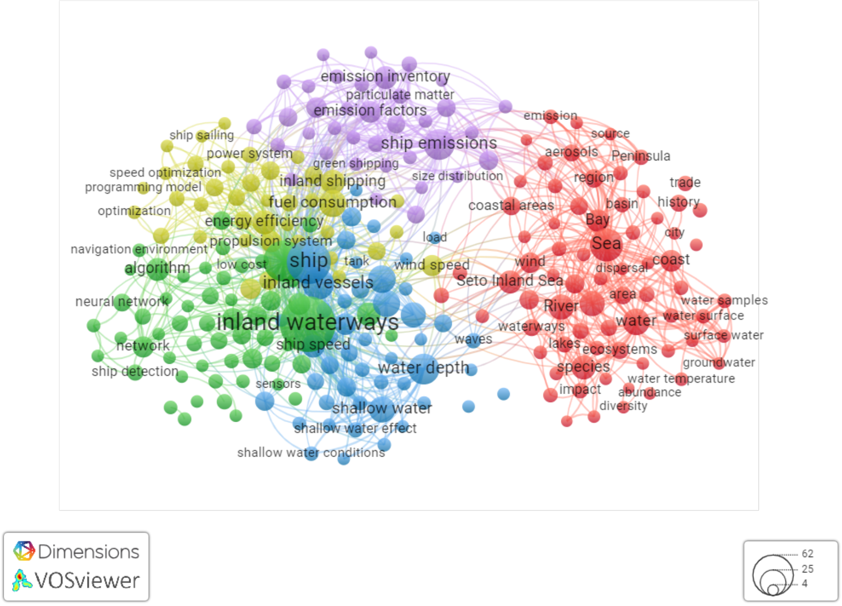

Figure 1: Literature clustering from database

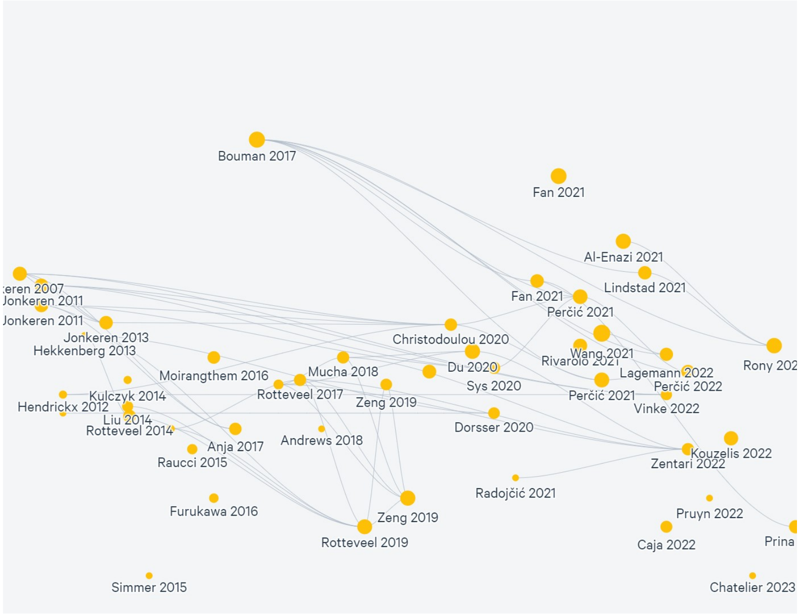

Figure 2: Map of reviewed literature

For the final review, 63 papers were studied in depth to arrive at the current state of the art, which will be presented next. The review is divided into two sections: the first section, which is covered in Climate Change and Inland Waterway Vessels, presents the impact of climate change on inland waterway vessels and the state-of-the-art options for adaptation, whereas Decarbonising Inland Waterway Vessels discusses the state-of-the-art decarbonisation of inland waterway vessels.

Climate Change and Inland Waterway Vessels

Climate change threatens the competitiveness and reliability of inland navigation, which also challenges the realisation of one of the objectives of the EU project NAIADES III action plan (Sys et al., 2020), which is to shift the significant share of freight transport from roads to more sustainable modes, such as inland waterways and rail transport. Several investigations have been conducted on the impact of climate change on inland water transport, and it is also interesting to note that many of these studies focused on the impact of low water depth on navigable fairways, because prolonged periods of droughts are expected to occur more often in the future and have even more severe consequences on efficiency, safety, and reliability than problems associated with high water levels or discharge on the fairways (Jonkeren, 2009). In many of these studies, various models were developed to predict the fairway conditions, estimate the hydrodynamic performance in shallow water, economic models to estimate revenue loss due to loss of payload capacity, and estimate the potential of modal shift from inland water transport to roads. In this section, we discuss the most prevailing impact of climate change on inland waterway vessels covered by current and past literature.

Resistance and Power Demand

Water depth severely impacts the resistance and power demands as this increases with decreasing water depth according to (Radojčić et al., 2021). ITTC, 2017 outlined that the shallow water effect on ship resistance must be taken into account when one or the combination of the following thresholds are met;

- Finite water depth to vessel draught ratio $h/T < 4$.
- Froude number of water depth $F_{\mathrm{nh}} > 0.5$.

According to (Radojčić et al., 2021), total ship resistance of inland waterway vessels can be decomposed into two categories; the viscous resistance and the wave-making resistance (see equation 1). Zentari et al., 2022 did highlight that, when $F_{\mathrm{nh}} < 0.6$, which characterises a subcritical flow regime, the wave-making resistance of a vessel in shallow water is comparable to deep water conditions. However, shallow water effect on wave-making resistance becomes more pronounced when the vessel approaches a critical flow regime of $F_{\mathrm{nh}} = 1$. Nevertheless, this is not the case for inland waterway vessels given that most of these vessels operate within a speed range below the critical regime (Zentari et al., 2022). As such, viscous resistance emerges as the most dominant resistance component of inland waterway vessels, where the influencing factors are the friction coefficient and hull form factor.

In shallow water navigation, the keel clearance, which is the safety distance between the hull bottom and waterway bed is considerably reduced. This consequently causes ship squat, also known as dynamic sinkage, which as a result of increased water flow around the hull, leads to reduced pressure below the hull, a phenomenon based on Bernoulli principle (Radojčić et al., 2021; Zeng, 2019). The squat further amplifies the frictional resistance (Zeng et al., 2017), due to thinner boundary layer resulting from accelerated under-keel flow. The power required to propel the vessel depends on the total resistance and the ship's speed (see equation 2). As such given an increase in ship resistance as a result of shallow water, for the same sailing speed, the ship would require more propulsion power to perform its functions, and this translates into more energy consumption. Alternatively, for a given installed power, the speed may have to be reduced, and as a result, more time may be required to transport cargo over a distance (Schweighofer et al., 2022), which also translates into more energy consumption.

$$R_{\mathrm{T}} = R_{\mathrm{V}} + R_{\mathrm{W}} \tag{1}$$

$$P_{\mathrm{E}} = R_{\mathrm{T}} \cdot V_{\mathrm{s}} \tag{2}$$

In recent years, numerical methods using computational fluid dynamics (CFD) simulation tools have been used for both predictions and optimisation of ship resistance [9]. The traditional, model scale tests and use of empirical models such as the Holtrop & Mennen have been used for resistance estimations with some correction factors, applied to ship speed and form factor (Pompée, 2015), to account for shallow water effects. However, the Holtrop & Mennen empirical model was fundamentally obtained from datasets of ocean-going ships and hence applying this to inland water vessels may lead to inaccurate predictions. Moreover, the Schlichting (1934) empirical method was based on speed correction to account for the deviation of residual resistance in shallow water compared to the deep-water case (Pompée, 2015; Raven, 2012). The Schlichting speed correction method was further improved by Lackenby (1963) by extending its application to extreme shallow water conditions (Raven, 2012; Zeng et al., 2017). Jiang (2001) proposed another approach to estimate the shallow-water effect, based on effective Froude number influenced by dynamic sinkage (ship squat) to predict a new effective speed of the vessel. The weakness of these empirical methods is that they rely on correcting the resistance curve in deep water for shallow-water scenarios of ocean-going vessels.

Given that the presence of channel walls and the shallow nature of inland waterways significantly impact the hydrodynamic resistance of inland water vessels at a given speed. Rotteveel (Rotteveel & Hekkenberg, 2015) stated that the limited breadth of the waterway leads to backflow around the vessel, increasing the water speed around the hull and thereby amplifying frictional resistance, which is termed as the hydraulic effect. Additionally, the restricted water depth limits the wave speed, causing increased resistance from wave formation at the ship's specified speed, which is termed the undulatory effect (Pompée, 2015). For the reasons identified above, the empirical methods with shallow water corrections derived from seagoing vessels are characterised by higher speed and lower block coefficients, adding to the fact that the environment in which they operate differ considerably not only in terms of depth but also breadth and the presence of canals and locks. These methods may not be sufficient for application in inland waterway vessels. Hence, using CFD methods, recent studies (Zeng et al., 2019) and (Raven, 2012) focused on predicting the shallow-water effect on the frictional coefficient. While Furukawa et al., 2016 focused on predicting the hull form variation and shallow water on the viscous component of the total resistance of inland waterway vessels. Table 2 summarises recent studies performed to accurately estimate the resistance components of inland waterway vessels, accounting for shallow water effects.

Table 2: Summary of recent literature on shallow water effects on resistance of inland vessels

Reference	Method	Key findings
Zeng et al., 2019	Regression numerical friction line for shallow water correction obtained from CFD simulations.	Authors find that this method can be used to better estimate the frictional resistance of the ship's flat bottom (parallel middle body), however, should be combined with the ITTC57 correlation line for other wetted surfaces for accurate estimation of overall frictional resistance in shallow water conditions
Rotteveel and Hekkenberg (2015)	CFD approach to investigate the effect of hull form variation (block coefficient) and shallow water on resistance.	The authors' viscous pressure resistance component increases faster in shallow water than frictional resistance. Also, the water depth effect is larger than the hull form variation on the total ship's resistance as an effect of the hull for variation rather becomes smaller in shallow water.
Zeng et al., 2017	Numerical and experimental methods to investigate dynamic sinkage and ship resistance in extreme shallow water.	The authors found that flow under the keel accelerated as keel clearance reduced leading to a thinner boundary layer which increased the frictional resistance component. And this is further amplified by trim and squat effects. The trim correlation line was not linear or monotonic, and a piecewise function might best be used to represent the relation between trim and ship speed.

Table 2 continued

Furukawa et al., 2016	Captive model test to estimate the longitudinal hydrodynamic forces acting on bare hull in sufficient and shallow water conditions, to measure the shallow water effects on the longitudinal components of hydrodynamic derivatives.	Based on the results from the database of test cases performed on multiple types of vessels. The authors derived an empirical formula for estimating longitudinal hydrodynamic forces acting on a vessel.
Raven, 2012	CFD approach Using PARNASSOS, a RANS solver developed by MARIN to estimate the viscous resistance of 4 different ships accounting for shallow water effects.	The variations of viscous resistance against water depth were determined by the computational model. The authors also found a correction for model-to-full ship extrapolation of the viscous resistance in shallow water. It was mentioned the Froude extrapolation and form factor extrapolation can be applied for full-scale frictional resistance prediction, however, may lead to overestimation of residual resistance at full scale.
Raven, 2022	Numerical computation approach by MARIN to establish correction factors independently for viscous resistance, a wave-making resistance and an overall added resistance due to squat effect for extremely shallow water conditions. The results were then validated with full-scale ship trials and empirical estimates.	The author found a limiting Froude number Frh < 0.65 for which there is no influence of water depth on wave-making resistance. It was also observed that overall resistance increased as a result of sinkage, which is present due to low pressure underneath the hull in shallow water. Although this sinkage effect was somewhat uncertainty, stating that the estimated increase in sinkage was too large, and therefore may lead to inaccurate prediction of the overall resistance.
Mucha et al., 2018	An experimental study of the effects of water depth, separation distance and bank effects on resistance of inland waterway vessels.	Result of this study revealed that sinkage was more pronounced with increasing ship speed and decreasing water depth. Also, lateral restrictions (proximity of vessel to the sides of the fairway) further lead to increase in lateral forces and moment (hydrodynamic sway and yaw motions). The magnitude of these lateral force and moment as noted by the authors can even exceed that of the longitudinal force required to move the vessel forward.
Zentari et al., 2022	An experimental and numerical investigation of shallow water effects on resistance and propulsion of coupled convoys.	Although authors recorded some deviation 15 % when comparing the numerical results of resistance to the experimental result in shallow water. It was found that in deep water, the boundary layer is fully developed, and flow separation zones are smaller, and less vortex shedding occurs, however, that is not the case in shallow water. In shallow water it was observed that the under-keel clearance influenced the boundary layer, thereby altering the velocity pressure field, causing flow separation.

Table 2 continued

Du et al., 2020	Numerical simulation of confined waterway effect on resistance and ship-generated waves of two inland waterway vessels.	It was observed from the simulations results that stronger confinements characterised by smaller cross-section area ratio between channel and ship, increase the ship resistance. This effect becomes even more evident with higher values of ship speed and higher loaded draft. Also investigating the wave pattern, it was noted that the wave propagation is limited by the channel banks and bottom, causing reflection and refraction. This effect was also seen to amplify with larger loaded draught.

Propulsive Efficiency and Manoeuvring Capability

The heightened power demand is further exacerbated by the reduced propulsive efficiency, which is a result of increased thrust loading on the propellers when operating in extremely shallow water (Radojčić et al., 2021). With reduced keel clearance, the inflow to propellers considerably differs from deep-water conditions, and as a result, affects the open-water efficiency coefficients (Radojčić et al., 2021). In addition to the reduced propulsive efficiency caused by high thrust loading owing to increased resistance when operating under low water conditions, the risk of propeller emergence or ventilation is also higher when sailing on reduced draught owing to the limited water depth, resulting in the loss of thrust and low propulsive efficiency (Hagesteijn et al., 2015). The hydrodynamic propulsive efficiency applied to ocean-going ships is fundamentally the ratio of effective power (P_E) and the power delivered to the propeller through the shaft (P_D), as defined by (Radojčić et al., 2021) in equation 3:

$$\eta_\mathrm{d} = \frac{P_\mathrm{E}}{P_\mathrm{D}} = \eta_\mathrm{H} \cdot \eta_\mathrm{o} \cdot \eta_\mathrm{R} \tag{3}$$

$$\eta_\mathrm{H} = \frac{1-t}{1-w} \tag{4}$$

$$\eta_\mathrm{o} = \frac{J}{2\pi} \cdot \frac{K_\mathrm{T}}{K_\mathrm{Q}} \tag{5}$$

The hull efficiency η_H and the relative rotative efficiency η_R, both describe the overall hull and propeller interactions. The action of the propellers behind the hull induces additional resistance to the entire ship resistance. Consequently, an additional thrust force is required to overcome the ship towing resistance, and the added resistance is measured by the thrust deduction factor t. Also, for IW vessels navigating in restricted water, the changes in the inflow to the propeller tend to increase the wake fraction w. And if the wake fraction w becomes larger than the thrust deduction coefficient t, the hull efficiency increases according to (Rotteveel et al., 2017) and confirmed by research results of MARIN in (Mucha et al., 2018). However, this phenomenon is a complex one, given that, an increase in wake fraction means a reduction in advanced speed (V_A), translating into a reduction in open water efficiency η_o and relative rotative efficiency η_R, which could ultimately even lead to an overall reduction in propulsive efficiency η_d (Radojčić et al., 2021). An interesting observation by (Rotteveel et al., 2017) of the wakefield, is that the nominal wake fraction w which is usually estimated without the presence of propeller may lead to low power estimation, given that the presence of propeller suppresses the growth of wake and flow separation. Therefore, an effective wake fraction w_e, accounting for propeller action is rather accurate for estimating power.

Pompée, 2015 highlighted that, given the high block coefficient of inland vessels around 0.85 and 0.95, the wake fraction could easily be twice as high as that of ocean-going vessels. The high wake fraction value which is characterised by low inflow speed to the propeller is very difficult to measure as noted by (Rotteveel et al., 2014), that simply approximating with empirical formulas may give misleading results. Howbeit, according to (Pompée, 2015; Rotteveel et al., 2014), methods like the Holtrop & Mennen and Papmel commonly utilised in naval architecture for predicting propulsion efficiencies through thrust and wake fractions, primarily cater to ocean-faring ships, overlooking considerations for IW vessels. The extended version of the Papmel formula was modified by A.M.Basin & Miniovich for inland vessels and pushers to accommodate inland vessels and pushers has been observed by (Pompée, 2015) and (Raven, 2022) to lack the incorporation of water depth effects. Most recently Rotteveel in (Rotteveel, 2019) analysed the influence of stern shape under varying waterway conditions on the propulsion performance of inland waterway vessels, this and other recent research have been summarised in Table 3 below.

Table 3: Summary of most recent literature on shallow water effect on inland waterway vessels propulsion

Reference	Method	Key findings
Rotteveel, 2019	In his thesis, Rotteveel used the CFD computation approach to analyse, the influence of stern shape variation of IWV on propulsion performance under different operating conditions. Further surrogate models were used to find trends and patterns for optimal design from the CFD results.	The author introduced novel design guidelines aimed at achieving an optimal stern design for efficient propulsion in low water conditions. This optimization process entailed balancing trade-offs between the ship's displacement and its propulsive performance across varying water depths. Through iterative adjustments of variables to attain the optimal design, the study identified the pivotal significance of stern length and the athwartship propeller position in enhancing propulsion efficiency.
Rotteveel et al. (2017)	Inland ship stern optimisation in shallow water. Optimising propulsion power based on aft-ship hull parameters which include; the lateral position of the propeller, stern bottom shape (V-shape and S-shape), stern bilge radius, and tunnel curvature.	It was observed the lateral propellers' position closer to the centerline, moves the propellers in a stronger wake field yielding increased hull efficiency. The V bottom shape showed stronger effect (increase) in thrust deduction compared to the S bottom shape in shallow water. The effect of the tunnel curvature was observed to be small and negligible with changing water depth. Also, the influence of the bilge radius was observed to decrease in shallow water, owing to the fact that in shallow water, the flow comes from the sides instead of the bottom.
Kulczyk and Tabaczek, 2014	Analysis of results of model tests, and numerical computation of the influence of ship loading, water depth, ship speed and stern height on thrust and wake coefficient for inland waterway motor cargo vessels and pushboats with stern tunnel	The authors found that both increase in ship speed and reduced h/T leads to decrease in wake fraction and corresponding increase in thrust deduction, owing to the reduction in under-keel clearance.
Hagesteijn et al., 2015	Model scale test in a Depressurized Wave Basin, to assess the performance reduction due to propeller ventilation.	Authors found from the experiment, speed reduction of 0.5knot due to ventilation. It was observed that, when propellers suck in air, the achievable thrust and torque required drop for a given advance coefficient. The resulting reduced thrust is sufficient to propel the vessel such that speed loss is inevitable.

The ideal design of propellers for IW vessels, especially to adapt to low-water conditions, as emphasised by (Hekkenberg, 2013), should be determined on a case-by-case basis. This involves finding a "sweet spot" such that, the propeller is small enough to remain fully immersed in water on the ballast draft, and also large enough to deliver sufficient thrust at the laden draft. This could also mean adopting the tunnel aft-ship to mitigate ventilation in ballast conditions or reduced draught imposed by low water depths; this was investigated by in (Rotteveel et al., 2017). However, (Hagesteijn et al., 2015) found that tunnel aft-ship does have added adverse effect on the hull resistance.

The manoeuvring and stopping capabilities of inland water vessels are also negatively impacted by shallow water effects. The change in hydrodynamic forces and moments acting on the hull and lifting surfaces influences the turning, stopping, and course-keeping performance, thereby compromising the safe operation of the vessel (Liu et al., 2014).

Cargo Capacity Utilisation

The loading capacity of inland water vessels is constrained by the available water depth. For a given ship size and dimension, the only variable that determines how much tonnes of cargo can be transported at a given time is the loaded draft, as the displacement in such instances depends on the depth of the vessel immersed in water. Total ship displacement can be decomposed into lightweight and deadweight; the deadweight tonnage is the component that determines the carrying capacity of the ship correlating directly to the loaded draft as investigated by (Hekkenberg, 2013) in a parametric inland ship design model. Given the draught restrictions imposed on vessels when navigating shallow water, the corresponding volume of cargo that can be transported is limited. The consequence of low water levels on the load factor differs for each ship type and size, depends on the vessel's empty and loaded draft (van Dorsser et al., 2020). The research findings from the EU joint research centre (JRC) in (Rothstein & Scholten, 2016), where they estimate the bearing capacity for different ship sizes and types, suggests that ships characterised by greater empty drafts are more prone to experiencing a reduction in their loading capacity at low level of water on the Danube river. In this work, for the lowest recorded water level of 177cm, the load factor of smaller vessels was about 50 %, whereas that of larger vessels ranged between 20 % and 30 %. Although not same quantified values of load factors were found by (van Dorsser et al., 2020) on the Rhine river, he also came to a similar finding that larger vessels experienced higher reduction and deadweight and payload capacity at low water levels.

Furthermore, a sensitivity analysis was conducted by (Al-Enazi et al., 2021), to deepen the understanding of the impact of capacity utilisation on the quantity of emissions produced. The findings revealed that an increase in capacity utilisation leads to a consistent decrease in CO2 emissions (Al-Enazi et al., 2021) per tonne-km. This is more related to the energy efficiency indices; an important operational performance metric, that quantifies carbon emission per transport work. Table 4 summarises recent literature on shallow water effects on cargo capacity utilisation

Table 4: Summary of the most recent literature on the effects of shallow water on cargo capacity utilisation

Reference	Method	Key findings
van Dorsser et al., 2020	Empirical model based on regression analysis of loading certificates of 157 ships, to analyse the relative effect of reduced or increased draft on loading capacity index	The model which was based on the operational loading of vessels during the extreme drought season of 2018, authors observed that vessels with higher empty draught are more vulnerable to low water conditions relative to vessels with low empty draft.
Rothstein and Scholten (2016)	Multi-regression analysis of the relation between water level and degree of capacity utilisation, transport volume per ship, total transport volumes and numberer of ships for transport on Danube river.	It was found from the analysis that, for every reduction in water depth by 10cm, the degree of capacity reduction was between (0.51 % and 0.66 %), for same water level reduction also, the transported cargo reduced by between (10t and 14t) for different ship types. Finally, also the total transported cargo on the corridor was observed to reduce in the range of (1188t and 3760t). For the lowest water condition recorded, they found from their model that smaller vessels could load about 50 % of their maximum capacity, whereas larger vessels only use up about 20 % to 30 %.

Vinke et al., 2022	Agent-Based and Discrete Event simulation using OpenCLSim; integrating hydrology data of corridor to estimate the cascading effects on navigation, transport performance, and economic impact	The authors observed a change in fleet composition with changing water levels, and also the number of trips required to make up for the volumes in normal conditions, although the simulation shows a loss of total transported volume

Transport Cost

The cost, among other factors, determines the competitiveness of inland water transportation. The restriction in the load factor, which results in reduced transport capacity caused by low water levels, leads to escalated transport expenses for the ship owner or operator. Moreover, (Jonkeren & Rietveld, 2007) says under certain demands, some negative relation between prices and water level is expected. These additional costs stem from the amplified voyage frequency, heightened handling expenses, prolonged waiting periods, and increased energy consumption. Consequently, these factors collectively account for a significant portion of operational expenditures (Jonkeren et al., 2013). Jonkeren, 2009 even found that the cost per ton could increase by as much as 75 % for vessels plying serious bottlenecks of the Rhine fairway at extreme water levels, noting that these additional costs are usually not borne by the operators or ship owners themselves, but the economic burden of low water periods is shifted to shippers and finally the consumers. As such shippers may consider alternative modes of transportation, potentially resulting in a decline in demand for inland water transport, and further worsening its competitive position (Krekt & van der Laan, 2011).

In a study conducted by (Jonkeren et al., 2011), the impact of prolonged drought on the cost of inland transport operations in Northwest Europe was evaluated. Their findings indicated that, in an extreme climate scenario, inland water transport could potentially experience a reduction in capacity of approximately 5.4 %. Furthermore, it was highlighted that road transport is likely to absorb a significant portion of this reduced capacity. Although (Krekt & van der Laan, 2011) also highlighted the potential loss of capacity to other transport modes due to climate change, they asserted that the majority of the shift would be towards rail transport, which contrasts the findings of (Jonkeren et al., 2011). Table 5 summarises recent literature on shallow water effect on the cost of cargo transport.

Table 5: Summary of most recent literature on shallow water effects on transport cost

Reference	Method	Key findings
Jonkeren and Rietveld, 2007	Multi-regression analysis to assess the impact of water level on the logarithms of load factor, freight rate per ton and freight rate per trip.	From the analysis of data on inland water transport activities on the Rhine River, authors found an empirical formula to estimate the welfare loss (economic implications) due to low water conditions between 2003 and 2005.
Jonkeren et al., 2011	Multimodal freight transport modelling with NODUS, a GIS-based software to assess the cost of transport operations for IWT over the Rhine River under varying climate scenarios	Authors discovered that the impact of extremely low water conditions extends beyond influencing the transportation prices of Inland Waterway Transport (IWT). These conditions may induce modal shifts, thereby compromising the competitive position of IWT in comparison to other modes of transportation.

Options for Technical Adaptation

To sustain competitiveness, cost-effectiveness, and reliability, it is imperative for inland water transport (IWT) to become less susceptible or more resilient to low-water periods, which are expected to become more frequent owing to climate change according to (Jonkeren, 2009). This necessitates a re-evaluation of vessel design trends, particularly for larger vessels that are inherently more vulnerable to low-water conditions (Radojčić et al., 2021; Rothstein & Scholten, 2016). From a design perspective, several research and development projects have been conducted to address the resilience of inland navigation to climate change. These projects consider technical adaptation measures aimed at efficient operation at a reduced draught, enabling flexible year-round navigation in both sufficient and shallow waters. Notable among them are concepts to achieve increased cargo capacity utilisation at reduced draught, by means of added buoyancy without altering the principal dimensions of the vessels. One of these concepts is the floatable side blisters investigated in the ECCONET project as referenced in (Zigic et al., 2012). The investigation of the concept of added buoyancy was further expounded and validated in the NOVIMOVE project (B. Ramne, 2021). In addition, measures to increase cargo transport on low draught by means of weight reduction, making use of lightweight materials for hull construction, were investigated in the INBAT project referenced by (Radojčić et al., 2021). Other options for maximising the capacity of a vessel by altering the principal dimensions of the ship have been investigated by (Bačkalov et al., 2016) and (Guesnet et al., 2014). To compensate for the loss of deadweight owing to shallow draught, it is possible to increase either the length or breadth of the ship. Bačkalov et al., 2016 noted that 'beamy' container vessels are more favourable than "lengthy" ones on restricted waterways, although the extent of beam increase is limited by canal and locks spaces on the fairway.

In a general context, it can be inferred from the previous subsection that operating under conditions of low water levels results in an increase in the thrust loading coefficient. Consequently, the open water efficiency is reduced, and when the draught is extremely low, the risk of propeller ventilation is high, impeding the generation of the thrust necessary to propel the vessel in water. The reduction in propulsive efficiency can be addressed by the concept of distributed thrust which was investigated by the notable STREAMLINE research project (Hagesteijn et al., 2015). Within this project, a novel design with six (6) thrusters was developed to attain higher efficiency at low propeller loading. The configuration of these propellers is such that forward propellers accelerate the flow to the trailing ones; at the same time, these propellers generate thrust instead of adding to the total ship resistance, as is the case with tunnels. The stern design is also such that the forward propellers again avoid flow separation and hence reduce the risk of propeller ventilation. In this research, for lower draughts, a new concept is proposed for streamlined cover plates to be fitted to prevent propeller ventilation which was originally investigated by DST. Given the relatively long lifespans of inland water vessels, climate change predictions must be factored into their design and planning. The careful design of the hull and propulsion, power, and energy (PPE) system configuration is imperative when accounting for low-water conditions in the early design phase (Kempmann et al., 2023). Table 6 summarises some notable adaptation measures and their application scenarios, as found in the state-of-the-art research projects and literature.

Table 6: Summary of Notable EU projects on Inland Waterway Vessels shallow-water adaptation

Reference	**Adaptability Measures**				**Application Scenarios**	**Key findings**
		Payload increase				
	Suitable Propulsion	*Additional buoyancy device*	*Lightweight construction*	*Beamy*		
ECCONET - Zigic et al., 2012	✓	✓	✓		Self-propelled cargo vessels	Retractable side blisters to increase buoyancy enabling improved cargo load factor at a reduced draught. Also, the use of high-tensile steel and aluminum was proposed to reduce the ship's weight

Table 6 continued

NOVIMOVE - B. Ramne, 2021			✓		Self proplled dry cargo vessel	Innovative Vessel concept, with added buoyancy to transport more cargo in shallow water conditions. Modular inflatable airpads which can be couple to the vessel's sides when needed to provide additional buoyancy during periods of low water levels.
VERBIS - Radojčić et al., 2021		✓	✓		Self-propelled cargo vessel and pushboats	Optimal hull form design for maximum payload at draughts. Also, a pump-jet propulsion was developed for push boats with draught (0.8-1.7m) to allow for shallow water operations
INBAT - Radojčić et al., 2021	✓			✓	Push boats and barge train	The application of lightweight construction materials and structural design was developed, realising weight saving of around 40 % if steel sandwich panels were used for small barge. Complimented with an innovative retractable middle propeller for additional thrust and manoeuvring during low draughts.
STREAMLINE - Hagesteijn et al., 2015	✓				Self-propelled Rhine class cargo vessel	A novel concept of distributed propulsion systems, offering efficient navigation advantage in extreme conditions. Although this comes with higher cost of investment, it offers the advantage of cheaper and smaller engines (usually road truck engines), which are also easier to maintain and replace. With the new stern design for 6 rudder propellers, it was also found that the cargo carrying capacity of the vessel could increase up to 3 %. In comparison with the reference vessel, an open water efficiency improvement of 21.5 % was recorded
IDV - Guesnet et al., 2014	✓			✓	Self-propelled container vessels for the Danube River	For the container vessel, the proposed concept is to increase the breadth of a standard 4-row container vessel from 11.4m to 11.65m to allow loading of 2.5 -2.55m wide domestic containers beside ISO containers, stowing up 2 tiers of container at 1.7 low draught. Also, for this concept, the author proposed an azimuth propeller for excellent manoeuvring optimised for low draught.
X-type - Bačkalov et al., 2016				✓	Self-propelled container vessels for the Danube River	The unconventional X-Type container vessel design. Increasing the breadth of a standard Class Va inland vessel carrying 4-row containers from 11.4 to 13.9 to stow an additional row. Increasing the beam was chosen over lengthening, for structural and cost considerations

Summary of Climate-Change Impact on Inland Waterway Vessels

The subsections Resistance and Power Demand to Transport Cost discussed the thematic literature on the state-of-art impacts of low water levels due to climate change on inland waterway vessels. The cascading effects could lead to a delay in the supply of goods, increased sailing time owing to reduced speed, and high transport costs for the given voyage, This culminating in an overall loss in transport efficiency and compounded by the undesirable modal shift to other transport modes with implications on the competitiveness of IWT. Identifying the main challenges, Options for Technical Adaptation, summarises some notable research projects and studies on adaptation measures to make inland waterway vessels more resilient to climate change. These projects primarily sought to address the issue of loss of cargo capacity utilisation with novel concepts to transport sufficient cargo even at low draughts. Additionally, they explored the concepts of suitable propulsion systems to ensure navigation at both low draught and normal laden draught conditions. Moving on, the next section discusses the state-of-the-art decarbonisation of inland waterway transport and the current state-of-the-art report on greening pilot projects within the European region.

Decarbonising Inland Waterway Vessels

The EU stage V emission limits, which are sets of regulatory requirements established by the European Union, are considered the world's strictest emission standards for non-road mobile machinery (NRMM). These standards, outlined in Regulation (EU) 2016/1628 (Shao et al., 2016), set specific limits for the levels of local pollutants, including particulate matter (PM), nitrogen oxides (NOx), hydrocarbons (HC), and carbon monoxide (CO), emitted by new IWV engines higher than 300 kW. The current approach to curb the environmental footprint of inland water fleets is achieved through internal combustion engines fitted with exhaust filtering systems. Nevertheless, the most challenging aspect is reducing GHG emissions, which have global warming potential (GWP) and ozone depletion potential, by way of absorbing infrared radiation. The main anthropogenic GHG gases, according to, are;

- Carbon dioxide (CO_2) accounts for approximately 76 % of the total GHG emissions.
- Methane (CH_4) accounts for approximately 16 % of all GHG.
- Nitrous oxide (N_2O) accounts for approximately 6 % of all GHG.

Greenhouse gas (GHG) emissions emanating from ships primarily stem from conventional fossil-based fuels that are extensively employed as the primary energy source for ship propulsion, with carbon dioxide (CO_2) being the predominant gas. Nevertheless, the use of liquefied natural gas (LNG) as a fuel introduces emissions of methane (CH_4), whose environmental impact is significantly more potent than that of CO_2. It has been observed that there is a wide range of technical and operational measures with significant emission abatement potentials. Independent options and combinations of options may provide enormous benefits. The feasibility of the options, as highlighted by (Finney et al., 2022), is dependent on the vessel types and their operations. A typical example is an optimal hull design combined with the use of hull air lubrication, primarily focusing on reducing ship resistance during operation, which in essence reduces power demands and, hence, energy consumption. This can contribute to improving energy efficiency and CO_2 emission reduction, but (Bouman et al., 2017)[48] illustrates that its potential as a single measure may be limited. Although many abatement options are mutually exclusive, such that they are not practically and economically feasible to be adopted in combination with other options, others may need to be combined with other options to significantly contribute to emission reduction (Bouman et al., 2017). According to life-cycle (LCA) studies, the primary source of adverse environmental outcomes throughout a ship's life cycle is identified as the operating phase (Al-Enazi et al., 2021), with energy consumption emerging as its largest contributor. Consequently, the transition to greener alternative energy sources is regarded as a viable approach to attain environmental sustainability objectives, offering up to 100 % emission reduction.

State-of-the-art of IWV Greening Projects

The SYNERGETICS [1] project has been tracking and compiling a database of pilot projects and developments of inland water transport decarbonisation within Europe, and so far, a total of 115 diverse types and classes of inland waterway vessels are being retrofitted or newly built. Throughout these projects, the main sustainable alternatives considered of interest for the IWT are LNG, biofuels (FAME, HVO), methanol, hydrogen, and batteries (see Figures 3 and 4).

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[1] https://www.synergetics-project.eu/downloads/

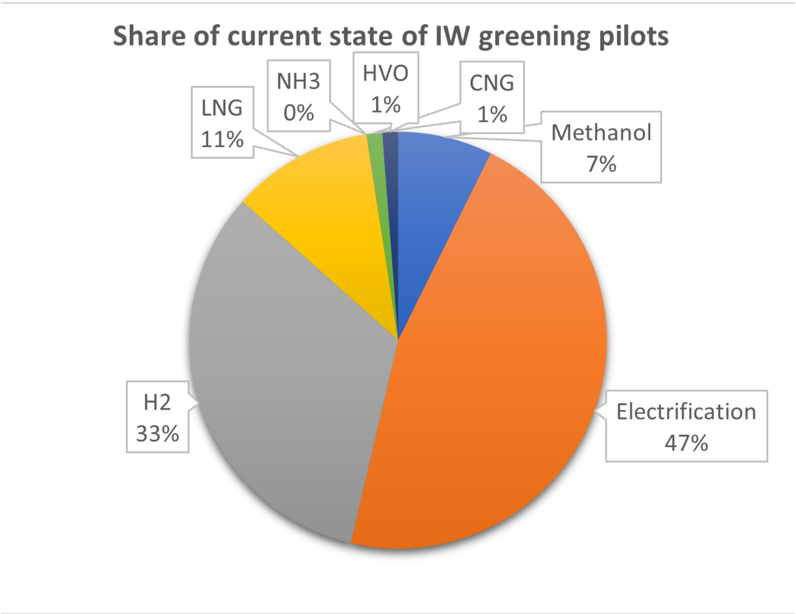

Figure 3: Shares Greening of IWV pilots in Europe

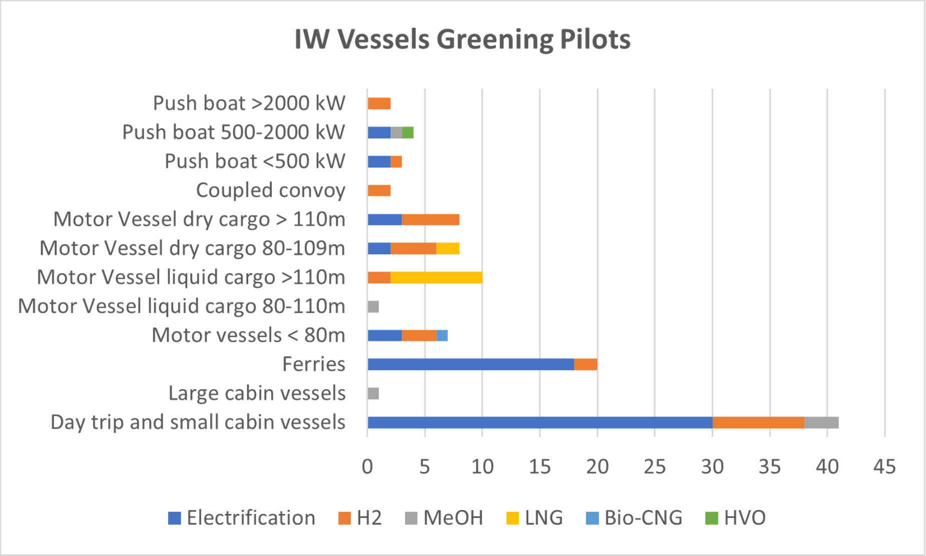

Figure 4: Classification of vessels and types of energy adopted for greening pilots.

Evidently, there are no ammonia-related projects, fundamentally because of toxicity and associated risks for IWT. A larger share of these projects is electrification, as shown in Figure 4, and the types of vessels that adopt batteries are those for short trips, such as day trip vessels and ferry boats.

Alternative Energy for Inland Waterway Vessels

The power train of a vessel is a system carefully designed to propel the vessel in water, primarily consisting of fuels as an energy source, internal combustion engines as convertors, and propellers as the device that produces thrust. Recognising the importance of tailoring newbuilds and retrofit solutions to specific vessels based on their operational profiles and power demands, it is necessary to explore viable options for alternative energy and power systems. Several studies have compared alternative propulsion, power, and energy (PPE) options based on their, environmental performance and economic viability, as well as the technology maturity. Table 7 summarises key literature on alternative fuels for inland navigation.

Table 7: Some key literature on Inland Water Vessels decarbonisation

Reference	Study	Alternative energy carrier	Key findings
Perčić, Vladimir, and Koričan, 2021	Electrification of Inland Waterway Ships Considering Power System Lifetime Emissions and Costs	Batteries	From the LCCA study on a cargo vessel, although electrification offered low environmental impact, it was found by the authors that reducing battery capacity onboard due to limited available space required reduction of sailing distance consequently extending the voyage duration by about 6 times hence the life cycle cost does not favour electrification for a cargo vessel. On the other hand, due to the lower required endurance of passenger ships, PV battery was found as most economical for passenger vessel, suggesting that electrification was more feasible for sustainable transition of passenger fleets.
Simmer et al., 2015	Multi criteria assessment of LNG as fuel for Inland Navigation	LNG	In considering the technical, logistic, financial, and environmental influence of adopting LNG as alternative fuel for inland navigation. Authors suggested that, the main factors influencing the adoption of LNG is the cost of investment, and regulatory barriers, although it was pointed out that the environmental gain are minimal and that because of methane slip.
Perčić, Vladimir, and Fan, 2021	Techno-economic assessment of alternative marine fuels for inland shipping in Croatia	LNG / Methanol / B20/ Hydrogen / Ammonia	The LCA revealed that the most environmentally friendly option is an electric powered vessel, however from the LCCA resulted in methanol as the most cost-effective option. A sensitivity analysis also showed that the not only does speed reduction influences the environmental performance of the alternatives, but also it influences the total cost of ownership. Indicating that although battery is the most expensive solution, reducing the speed by 30 % would result in 51 % reduction in net present value (NPV).
Rivarolo et al., 2021	Multi-criteria comparison of power generation and fuel storage solutions for maritime application	Hydrogen / Ammonia / Methanol / LNG	Comparative analysis based on weight, volume, cost, and emissions revealed, that the weight and volume limitations are more pronounce in the choice of alternative power and energy system than the emission reductions, given that this significantly reduced cargo loading and hence the revenue stream of the vessel.
Taccani et al., 2020	High energy density storage of gaseous marine fuels	Hydrogen	Efficient onboard storage containment for hydrogen fuel. The newly design storage "GASVESSEL" cylinders, requires volume of about 15.2m3 and total weight of 2.5 ton to store 140kg of hydrogen, compared to the type 1 cylinder which would have require 28m3 and 12.3 tons. This was a significant saving of about 2 time and 5 time in terms of space and weight respectively.

Table 7 continued

Prina et al., 2023	Optimal fleet transition modelling for sustainable inland waterways	Batteries	Analysing the fleet composition of small electric passenger boats required to replace diesel powered passenger boats on the Orta lake. Authors found that the number of charging stations and the capacity of these station play a critical role in determining the fleet composition required to replace existing fleet. It was concluded that with higher charging capacities of the stations, the entire diesel fleet can be replaced with equal number of new electric fleet without changes to the routes and travel scheduling, however with lesser charging capacity along the fairway, more vessels were required to replace the diesel fleet
Perčić et al., 2023	Holistic energy efficiency and environmental friendliness analysis of inland ships with alternative power systems	LNG / Batteries / Methanol / Hydrogen / Ammonia	Assessing the life cycle GHG and local pollutant (NOx and Sox) emission performance of cleaner fuels for inland navigation, it was established that batteries offer better GHG footprint, however batteries contribute significantly to SOx emission during its manufacturing phase. Although the NH3 and H2 do not produce tail pipe emissions, their current production from fossil fuel results in significant GHG pollutions.
Moirangthem and Baxter, 2016	Alternative Fuels for Marine and Inland Waterways	Biofuels / Hydrogen / Methanol / Batteries	This study suggests that LNG and Methanol could serve as transition fuels for mid-term, before making a major shift to cleaner fuels such as biofuels.

Challenges with Choice of Alternatives

Transitioning to cleaner energy and power systems for inland navigation is not devoid of challenges. The subsequent subsections shed light on the key hurdles associated with opting for alternative energy sources in inland navigation.

- **Space and weight requirements**
  A challenge related to the choice of alternative power and energy systems for inland vessels is related to onboard storage and integration. As mentioned earlier, compared with conventional diesel fuel as a baseline, the low energy densities of these alternatives necessitate an additional volume or deadweight to accommodate the equivalent capacity of diesel fuel. The storage of gaseous alternative fuels presents challenges because of their considerable space and weight requirements. This issue is exacerbated by specific storage containment methods, especially for naturally occurring gaseous fuels, such as hydrogen and ammonia, which necessitate the use of cylinders. Taccani (Taccani et al., 2020)[53] in the GASVESSEL project illustrated this challenge, revealing that a 1.8-ton storage system is required to contain 140 kg of hydrogen at 25°C and 250 bar in a type I pressure vessel. Additionally, adapting cylindrically shaped tanks to fit existing rectangular spaces leads to the suboptimal use of space. Furthermore, safety considerations for handling and storing Methanol and ammonia impose non-negotiable constraints on where these fuels can be stored, further limiting the use of available space. Indeed, in an investigation by (Rivarolo et al., 2021), a comparative analysis was undertaken to assess various alternative energy carriers and their respective converters for a small river passenger boat. The evaluation criteria encompassed volume, weight, cost, and emissions. The results of their scoring revealed that the limitations associated with weight, volume, and opportunity cost exerted a more substantial influence on the choice of greening technology than emissions.
  In a similar study conducted by (Lagemann et al., 2022) on retrofitting a deep-sea bulk carrier, accounting for the loss of payload, was expressed as opportunity cost within the total cost of ownership (TCO). In this situation the loss of revenue due to payload reduction when hydrogen is adopted was more pronounced. These observations arise from the impracticality of achieving zero emission when the utilization of zero-emission technology significantly takes up

cargo space and adds to the deadweight of the vessel. This limits the cargo carrying capacity of the vessel, which is the primary function of the vessel and thus the revenue stream of the owner.

- **Range and endurance (bunkering frequency)**
  Ship range and endurance are defined in terms of the maximum distance a ship can travel on its loaded fuel capacity and the maximum time of continuous operation without refilling respectively. When the cargo capacity in terms of volume and deadweight is maintained, the energy capacity is then constrained to the available space and deadweight. Consequently, given the low volumetric and gravimetric energy densities of the alternative energy carriers, the quantities that can be carried onboard may not suffice the required range and endurance. As such, the ideal distance that the vessel may cover is considerably reduced, requiring intermittent bunkering to complete a voyage. An important performance metric that measures the transport efficiency of a vessel is the voyage time, which would be inevitably influenced by bunkering time and the frequency of bunkering required to complete a voyage. An example of this inefficiency was analysed by (Perčić, Vladimir, & Koričan, 2021), where it was found that reducing battery capacity due to limited available space, required a reduction of sailing distance consequently extending the voyage duration by about 6 times for an inland cargo vessel. Lower range and endurance become more challenging, particularly in situations where bunkering infrastructures are limited on a specific operating corridor.

Summary of Inland Waterway Vessels Decarbonisation

The subsection State-of-the-art of IWV Greening Projects highlighted the state-of-art green pilot projects within Europe, whereas Alternative Energy for Inland Waterway Vessels summarises recent studies on alternative energy carriers for inland waterway vessels. The subsection Challenges with Choice of Alternatives also underscored some pivotal challenges impacting vessel performance as a result of opting for alternative energy and power systems.

CONCLUSION AND FUTURE STUDY

Conclusions

In this study, we conducted a scoping literature review, summarising the state-art-of-the-art “sustainable and climate-resilient inland waterway vessels”. This study examines the multiple influences of climate change on vessels, as well as the problems associated with the choice of alternative energy on the performance of vessels. Altogether, this review first highlighted the most challenging impact of extreme shallow water conditions on the efficient operations of inland waterway vessels in terms of hydrodynamic performance and cargo transport performance, which threatens the ambitions to increase the modal share of inland water transport, that is already underutilised. Secondly, this work highlighted, the applicability of different alternative energy and power systems configurations on inland waterway vessels and how they also influence the performance of the vessel also in terms of cargo carrying capacity and voyage distance or endurance.

Fundamentally, there is yet to be found literature or study that takes into account, the dual facet problems of energy transition and climate-resilience of inland waterway vessel. These two have traditionally been tackled independently. While it is important to understand that the properties of the alternative energy carriers pose challenge to the overall transport efficiency of vessels, the impact of climate change on the conditions of the fairway also poses challenges to the transport efficiency of inland waterway vessels, and hence the need for both influences to be considered holistically. Having identified the gaps in the state-of-the-art, this presents an opportunity for further investigation, towards future-ready and climate-resilient inland waterway vessels.

Future work

To address the complexity of these challenges, a holistic approach in assessing the intricate interplay between these problems is crucial for consideration in early design stage. This comprehensive approach is important to find optimal design parameters for inland waterway vessels. The objectives of optimal design parameters are to ensure minimum energy consumption and maximise propulsive efficiency under different fairway conditions. Simultaneously, achieving maximum payload capacity, while maintaining a balance with the vessel's energy requirement and allowing cargo transport over longer range and endurance. Integral to this would be to concurrently ensure minimal environmental impact associated with the choice of alternative energy and power systems. This overall would ensure a harmonious balance between vessel performance and sustainability.

CONTRIBUTION STATEMENT

Author 1: Literature review and writing of manuscript. **Author 2:** Supervision, critical review and script - editing. **Author 3:** Supervision and critical review.

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