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Electrifying inland waterway transport – a case study for Germany

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ABSTRACT
Battery electric propulsion represents a highly promising avenue for the decarbonization of inland waterway (IWW) transport. This paper thus examines the potential for electrifying IWW vessels using their operational profile derived from Automatic Identification System (AIS) data. Therefore, a model is developed to derive the energy demands and operational profiles of IWW vessels, which is then used to quantify the potential for battery electric propulsion systems without any adjustments to the vessels' operational profile, thereby ensuring the continued economic operation of the vessels. Moreover, a linear programming model is developed with the objective of minimizing charger power, and its technical feasibility is evaluated. The findings indicate that hybrid battery electric systems can supply between 35% and 70% of the propulsion energy in the majority of vessels. The necessary charging powers typically fall within the range of 100 to 200 kW. It may also be feasible to implement a fully electric propulsion system for a proportion of the IWW fleet. In particular, small passenger vessels such as ferries exhibit considerable potential in this respect, with median battery sizes of 731 kWh and requisite charging powers of under 100 kW.

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Inland waterways; AIS; battery electric propulsion; linear programming; optimization; charging infrastructure

1. Introduction

Inland waterways (IWW) pose a great opportunity to make supply chains more sustainable. Compared to road based transport, they offer significantly lower emissions per transported unit of volume (European Environment Agency 2024). Nevertheless transport on IWW only accounted for 5.1% of all inland freight transport in the EU, where more than three quarters of goods were transported by road in 2022 (Eurostat 2023). The European strategy for low-emission mobility encourages a shift towards lower emission transport modes (European Commission 2016), which could result in a higher transportation volumes on the IWW. However currently 95% of all inland vessel use diesel powered engines as their primary energy source which still causes high emissions of greenhouse gasses and other pollutants (Fan et al. 2021). In order to reduce the emissions of IWW transport, alternative means of propulsion must be adopted. A number of pilot projects are currently underway, testing alternative propulsion systems on vessels operating on the IWW. The research project ELEKTRA tested a hybrid propulsion system using a hydrogen fuel cell and a Li-ion MMC battery system on an inland push boat (Haase et al. 2020). Furthermore, the Dutch company Future Proof Shipping is retrofitting inland barges with hydrogen fuel cell systems with the objective of constructing a fleet of 10 zero-emission vessels (Future Proof Shipping 2024).

In addition, there are a number of other possible propulsion systems for decarbonization of IWW vessels. Therefore, Perčić et al. (2020) conducted a life cycle analysis of various propulsion systems for use on the Croatian IWW. Their findings indicated that, across all test cases, battery electric propulsion yielded the most favourable results, with the potential to reduce the vessels' carbon footprints by up to 51%. Despite the potential battery electric propulsion systems could pose for specific application within the maritime industry, there is still limited research with regards to this topic. The BSR electric consortium (BSR Electric 2020) studies, among other things, the implementation of electric ferries in the baltic sea region. They conclude that battery systems are particularly advantageous for ranges up to 10 km in inland and coastal waters. Furthermore, Anwar et al. (2020) highlighted different challenges for ferry electrification. According to the authors, one of the most significant technical challenges is providing the necessary power to the chargers, while not overloading the local electricity grid. Other studies have looked into designing fully electric powered vessels. Karkosiński et al. (2021) came up with an approach for designing an onboard energy storage and power

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management system for an all electric 1500 TEU container ship. According to the authors, such a ship could achieve a 250 km range in ‘zero emission mode’. An overview of current developments in battery storage systems for maritime applications can be found in Kolodziejski and Michalska-Pozoga (2023).

Investigations into solutions for electric propulsion systems on IWW vessels were conducted by Chatelier (2023). The author’s findings indicate that a range of suitable IWW vessels already exist, which would allow for the adoption of electric propulsion systems. Particularly vessels operating short distances such as ferries are well suited. Campillo et al. (2019) highlight the role of the increased adoption of electric road vehicles in reducing system costs with regard to electric propulsion systems. Furthermore, Prina et al. (2023) present a model for transition pathways to battery electric propulsion for tourist ferries in northern Italy. Based on a market assessment of the currently available technology, the model identifies the fewest number of vessels necessary to replace the currently operating fleet with a battery electric one. The authors highlight the importance of the charging infrastructure in determining the optimal fleet configuration and operation.

Consequently, there are still considerable challenges to overcome, particularly in relation to battery range and the availability of recharging infrastructure. Further problems include the significantly lower energy density and longer replenishment times of current battery technologies as compared to traditional fuels such as diesel. Careful planning and adjustments to the operational cycle of the IWW vessels may therefore be necessary for a proportion of the IWW fleet. This presents a considerable challenge to ship operators, as they already face difficulties maintaining competitiveness with road-based transport solutions, particularly in terms of speed, flexibility, and the level of service they can provide (Vilarinho et al. 2024; Krause et al. 2022). Yang et al. (2024) present a model to facilitate the scheduling of battery swapping operations for IWW vessels, with the objective of optimizing the total waiting time of vessels and their sailing speed. However, this approach would still entail a disruption of the established operational profiles of the vessels. Another way to offset this disadvantage is through hybrid systems, such as diesel-electric propulsion. Litwin et al. (2019) demonstrated that a hybrid system comprising battery-electric and diesel propulsion can be advantageous from both an economic and an ecological standpoint.

In relation to the above, the main aim of this article is to answer the question of which portion of the current IWW fleet can be electrified without significant changes to the operational profile of the vessels. Additionally, the technical requirements for the full electrification of the IWW fleet are evaluated. The answer to those questions could significantly contribute to the discussion of how to transform the IWW fleet to more sustainable modes of propulsion. To achieve this, the operational profiles of the vessels, in terms of energy demands and stopping times, are first derived from Automatic Identification System (AIS) data. Additionally, a model is developed to determine the necessary battery sizes and maximum charging power. The results are assessed in terms of their feasibility for the different ship types and operational profiles.

The rest of this paper is structured as follows: Section 2 lays out the materials and methods used in this study, especially with regards to the treatment of the AIS data. Furthermore, an optimization model is developed to minimize the necessary charging power. Section 3 presents the results with regards to the study area of Germany. A further discussion of the methods and results is provided in Section 4, after which the conclusions are summarized.

2. Materials and methods

The objective of this study is to quantify the proportion of the IWW fleet that could theoretically be converted to electric power for at least some of its operations. Hybrid diesel-electric propulsion systems as well as the potential for fully electric propulsion systems are considered. The present study is limited to vessels whose primary field of operation is within the IWW system. Consequently, vessels are filtered according to their assigned fleet type in the Clarksons World Fleet Register (Clarksons Research 2024). Only those classified as ‘Barge & Inland’ are considered. This encompasses both passenger and cargo vessels, as well as specialized ship types, including dredgers. Furthermore, all vessels of the type ‘Towing/Pushing’ are excluded from the analysis, as these vessels exhibit significant variations in energy demand with regards to the quantity of cargo they push. This is not always directly apparent from AIS data.

2.1. AIS data

In order to quantify the potential for battery electric propulsion systems, a commercial AIS data set is analysed for the pre-pandemic year of 2019. First, garbled messages are eliminated from the data. As pointed out by Sang et al. (2015), IWW vessels are widely using the Class-B AIS transponders, which have a lower transmitting power compared to the class-A transponders usually used for larger vessels (Fujii et al. 2014). This leads to increased garbling of AIS messages received form class B transponders (Norris 2006), which in turn can cause gaps in the data sets for IWW vessels (Figure 1). Gaps where the average speed of the vessel between the lost signal and the subsequent

Figure 1. Gaps in AIS data from a sample vessel (Map: © OpenStreetMap contributors).

reappearance of the signal is above 20% of its reference speed as listed in Clarksons Research (2024) are filled. Gaps larger than this are considered 'lost targets', since the vessels activities can no longer derived with confidence. After the data is cleaned, it is processed to determine the operational status of the vessels for each signal. The operational profiles of the vessels are categorized in either 'underway', ' manoeuvring', 'berth' or 'anchoring' according to the standards defined by the International Maritime Organization (IMO) (IMO 2020). Furthermore, the status 'waterlock' and 'bunkering' have been added to indicate when a vessel is detected passing through a lock or docked at a bunkering facility. Vessels with fewer than 1000 AIS signals on the German IWW system have been disregarded as either the quality of the data is insufficient or their total sailing time in Germany is considered too short.

Next the energy demand of the main and the auxiliary engines and the auxiliary boiler is calculated. The calculations are conducted in accordance with the Fourth IMO Greenhouse Gas Study 2020 (IMO 2020). The instantaneous propulsion power $\dot{W}_i$ of the ship is calculated by observing the instantaneous ship speed v_i and the draught t_i, which are taken from the AIS data. These are compared with the reference values from Clarksons Research (2024). The reference values W_{ref}, v_{ref} and t_{ref} serve as the basis for the calculation. For certain ship sizes and types, the correction factor δ_W is applied to take into account the usual oversizing of the propulsion power in relation to v_{ref}. The exponent of the admiralty formula m for the draught ratio is assumed to be 0.66, while the exponent n for the speed ratio is assumed to be 3. Additional resistance caused by the influence of weather conditions and hull fouling is taken into account by the mean influencing factors η_W and η_f.

$$\dot{W}_i = \frac{\delta_W \cdot W_{ref} \cdot \left(\frac{t_i}{t_{ref}}\right)^m \cdot \left(\frac{v_i}{v_{ref}}\right)^n}{\eta_W \cdot \eta_f} \tag{1}$$

The propulsion power is then multiplied by the time between two AIS signals in order to derive the energy demand. As there is a significant discrepancy in energy demand when a vessel is travelling upstream or downstream (Jiang et al. 2021), the direction of travel is also taken into consideration to improve the accuracy of the model. This is achieved by converting the speed over ground of the vessel into its speed through water. The data for the flow velocity is based on discharge models described in Hagemann et al. (2020) and Hagemann and Dümenil (1997).

2.2. Determining the electrification potential

With the energy demands determined from the AIS data, the electrification potential for the analysed vessels can be derived. To achieve this, the operational profile (e.g. Figure 2) of the vessels is broken down according to the use of the main propulsion system. Subsequently the two operational statuses 'sailing'

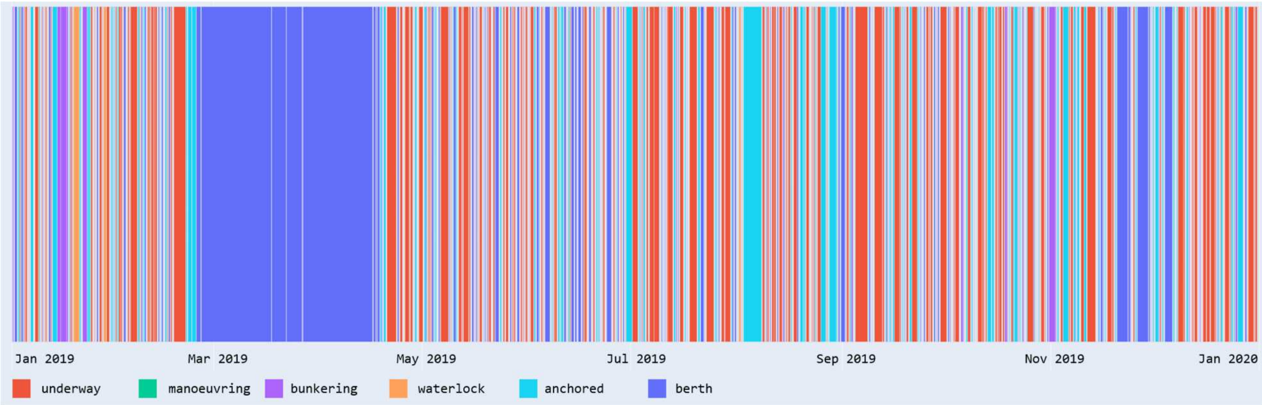

Figure 2. Operational Profile of a sample vessel.

(i.e. 'underway' or ' manoeuvring') and 'stopped' (i.e. 'berth', 'anchoring', 'waterlock' or 'bunkering') are left. A period where a vessel is sailing is referred to as a 'track' in the following'. A new track starts after a vessel has stopped. The energy demands of the individual signals within the track are summed up to a total energy demand for the whole track. Tracks containing 'lost targets' are eliminated from the data set. Since this paper only aims to derive electrification potential for the propulsion system, the auxiliary power demand is not considered. Two different forms of electric propulsion systems are analysed. A hybrid diesel-electric propulsion system and a fully electric propulsion system. The following sections will outline an approach to determine the potentials for both systems.

2.2.1. Diesel-electric-propulsion

Since the battery capacity required for fully electric propulsion may be significant, an approach to quantify the potential for a hybrid diesel-electric propulsion system is first developed. To determine the maximum capacity of each ships battery, the volume of the battery and its integration into the vessel needs to be taken into account. There are two different approaches to integrating the battery. The battery may be integrated in the form of an energy container, which can be swapped in order to reduce replenishment times. This solution would be applicable to cargo vessels that have sufficient space to accommodate such a container on deck. However, for river cruise ships or ferries, installing a permanently integrated battery system would be a more realistic option, which is why they are chosen for this study. This necessitates the vessel to charge the battery while it is stationary, resulting in longer replenishment times. Moreover, a greater impact on the electrical grid compared to energy containers is also likely. These can be charged independently of the vessels' movements and are therefore able to use lower charging powers. Additionally, the hybrid propulsion system itself must be considered. For this, a setup similar to that in Litwin et al. (2019) is assumed. Some companies (e.g. Wärtislä (2024)) already offer hybrid solutions for retrofitting larger vessels. It is feasible that similar solutions could also be applied to smaller vessels such as IWW ships. For the hybrid propulsion system, some assumptions regarding the installable battery capacities must be made. Here we define the maximum installable battery capacity on each vessel via the rated power of the main engine gathered from Clarksons Research (2024). The vessel should be capable of operating at full power for at least x hours before running out of energy. Therefore, the assumed capacity of the batteries installed on the vessels are calculated as follows:

$$C_{bat} = \frac{P_{eng}}{\eta_{Syst}} \cdot x \tag{2}$$

Where P_{eng} is the main engines rated power and η_{Syst} is the system efficiency of the battery and its management system. A system efficiency of 85% is assumed, which represents a conservative assumption and is already achievable with current technology (Kolodziejski and Michalska-Pozoga 2023). The maximum operation time x should be chosen so that the dimensions of the battery fit the space available on board the vessel. A reasonable assumption would for example be $x = 1h$. For the largest inland vessels analysed in this study, which are equipped with engines having an approximate power output of 3.5 to 4 MW (with some exceptions) (Clarksons Research 2024), this would result in a system that is comparable to the capacity of two state-of-the-art 20 ft container battery systems approved for use in maritime applications (Corvus Energy 2023). An upper limit for the battery capacity at 8000 MWh is also defined, which is equivalent to two 40 ft containers with the same battery system. The focus is on shore to ship charging rather than battery swapping operations. The maximum charging power is dependent on the vessels battery and its C-rate. To determine the initial electrification potential, the maximum C-rate considered here is 3, which is in line with other studies. Ghimire et al. (2021). The maximum charging power is therefore calculated for every vessel individually.

$$P = C_{bat} \cdot C_{rate} \tag{3}$$

For the initial calculations the assumption is made, that a minimum stop length of 10 minutes is required for a vessel to charge. Any stop shorter than 10 minutes is considered insufficient to charge the battery. The minimum state of charge (SOC) considered is 30%.

The energy demands of each track and the duration of each stop are used to calculate the SOC of the battery after each track. Battery propulsion is always preferred to diesel propulsion, if a sufficient SOC is left in the battery. If the SOC is less than 30%, the vessel uses its traditional diesel engine. A simplified linear charging curve is assumed. Figure 3 provides a flow chart of the steps carried out for every vessel and every track.

2.2.2. Charger power optimization

Once the initial electrification potential has been established, the power of the charging stations can be optimized. This is done to calculate the minimum required power ranges that must be provided by the grid in order to achieve the same electrification potential as calculated using the approach outlined in Figure 3. There, a charging power equivalent to the product of the battery capacity and the C-rate was assumed. This may result in very large chargers in the range of multiple MW. The minimal charger power is calculated by a simple linear programming optimization approach which minimizes the maximum charging power necessary in order to achieve the desired electrification potential. A set $\boldsymbol{I}$ is introduced depicting the set of all tracks for one vessel. The energy demand of each track $\boldsymbol{i}$ is E_i. P_i is the requisite charger power for track $\boldsymbol{i}$ and $E_{Diesel,i}$ is the power provided by the diesel engine. The stopping time after each track is t_i. In addition to the objective function (4), the model consists of 5 constraints ((5)–(9)). (5) is a flow constraint, (6) and (7) define the minimum (SOC_{min}) and maximum state of charge, (8) stores the maximum charger power P_{max} and (9) defines the maximum energy to be supplied by the diesel engine by linking it to the share of battery electric propulsion S_{bat} as calculated in Section 2.2.1. If a stop is shorter than the minimum charging time defined in Section 2.2.1, t_i is set to 0 during preprocessing.

$$\min P_{max} \tag{4}$$

s.t.

$$SOC_i = SOC_{i-1} + \frac{P_{i-1} \cdot t_{i-1}}{C_{bat}} + \frac{E_{Diesel,i}}{C_{bat}} - \frac{E_i}{C_{bat}} \quad \forall\, i \in I \backslash \{0\} \tag{5}$$

$$SOC_i \leq 1 \quad \forall\, i \in I \tag{6}$$

$$SOC_i \geq SOC_{min} \quad \forall\, i \in I \tag{7}$$

$$P_i \leq P_{max} \quad \forall\, i \in I \tag{8}$$

$$S_{bat} = 1 - \frac{\sum_{i \in I} E_{Diesel,i}}{\sum_{i \in I} E_i} \tag{9}$$

The model is solved for every vessel. From the results, the necessary C-rate for the battery can also be determined. The results from the model can than be analysed in terms of their technical feasibility.

2.2.3. Fully electric propulsion

Although a hybrid propulsion system is an effective means of reducing the environmental impact in the short term, it should be noted that certain vessels and routes may already be suitable for conversion to a fully electric propulsion system. This would result in a further reduction in emissions on the IWW. In order to facilitate this transition, the requisite battery capacities and charger powers are calculated with the aim of converting the analysed fleet to fully electric propulsion. For a vessel to run entirely on battery electric propulsion, it must be able to meet the energy demand of its longest track. The battery capacity is therefore taken as the energy demand of the longest track multiplied by a safety factor using the minimum SOC. The necessary charger power, can be calculated by a simple reformulation of the linear programming model developed in Section 2.2.2. The term accounting for diesel propulsion is removed from the flow constraint (5):

$$SOC_i = SOC_{i-1} + \frac{P_{i-1} \cdot t_{i-1}}{C_{bat}} - \frac{E_i}{C_{bat}} \quad \forall\, i \in I \backslash \{0\} \tag{10}$$

Furthermore, Equation (9) is removed from the model. The rest of the model remains as presented in Section 2.2.2. The results of the adjusted model can again be analysed in terms of their technical feasibility. It must however be noted that according to the European Standard Laying Down Technical Requirements for Inland Navigation Vessels (ES-TRIN) (ES-TRIN 2023), a redundant energy source (next to the battery calculated here) must be provided ensuring the vessels manoeuvrability in case of a system failure. This is not accounted for in the results of the model and needs to be taken into account when a fully electric propulsion system is installed.

3. Results

The present study is based on the IWW system in Germany (Figure 4). The total length of the German IWW system corresponds to more than 6500 km, with the Rhine being by far the most important IWW in Germany (BDB 2024). All ‘barge & inland’

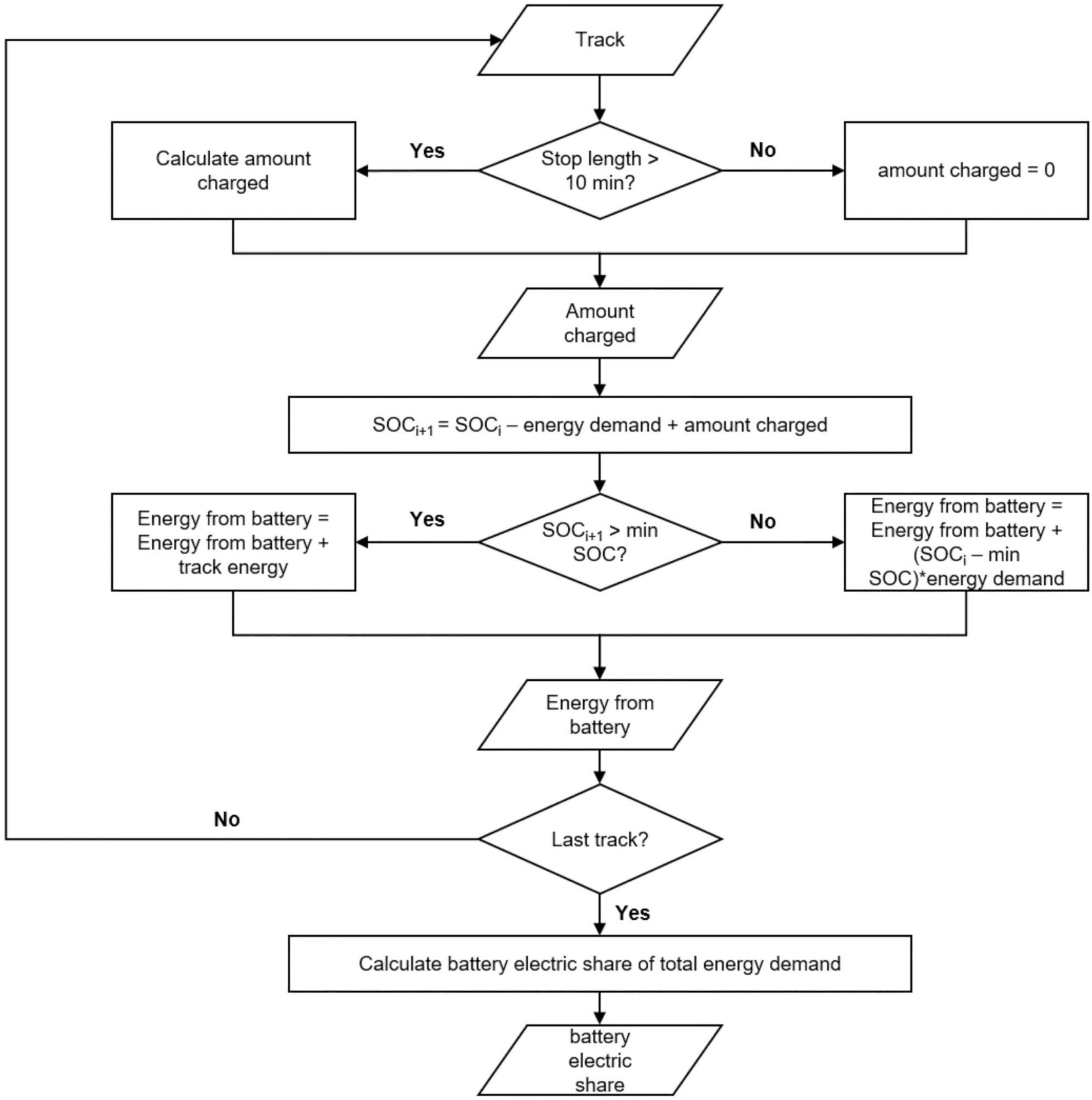

Figure 3. Flow diagram to calculate the battery electric share for every vessel.

vessels, except for push boats, that sailed on the German IWW network in 2019 and sent sufficient AIS signals, are analysed. In total AIS data of tracks from 2535 vessels over the course of a year is analysed. As mentioned before, tracks with large gaps are eliminated from the data set and are therefore not considered in the emission estimates. The makeup of the considered fleet can be derived from Table 1. The fleet was divided into passenger and cargo vessels. Cargo vessels where further subdivided into liquid and dry cargo and grouped by their overall length (LOA) according to the fleet families suggested by the Central Commission for Navigation of the Rhine (CCNR) (Kelderman et al. 2016).

The results are split into three parts. First, the potential for hybrid electric propulsion systems is analysed using the approach outlined in Section 2.2.1. Using those results, the minimum requisite charging power is derived applying the model developed in Section 2.2.2. Ultimately, the technological requirements for the complete electrification of the IWW fleet is determined through the application of the model adjustments outlined in Section 2.2.3.

3.1. Potential for hybrid propulsion systems

For the hybrid diesel-electric propulsion system, three different calculation scenarios are considered to understand the sensitivity of the results to various input parameters. The considered base case (case 1) is calculated as described in Section 2.2.1. Each vessel is assumed to be capable of fitting a battery electric propulsion system on board, which can supply the main engine with its rated power for 1 hour. This

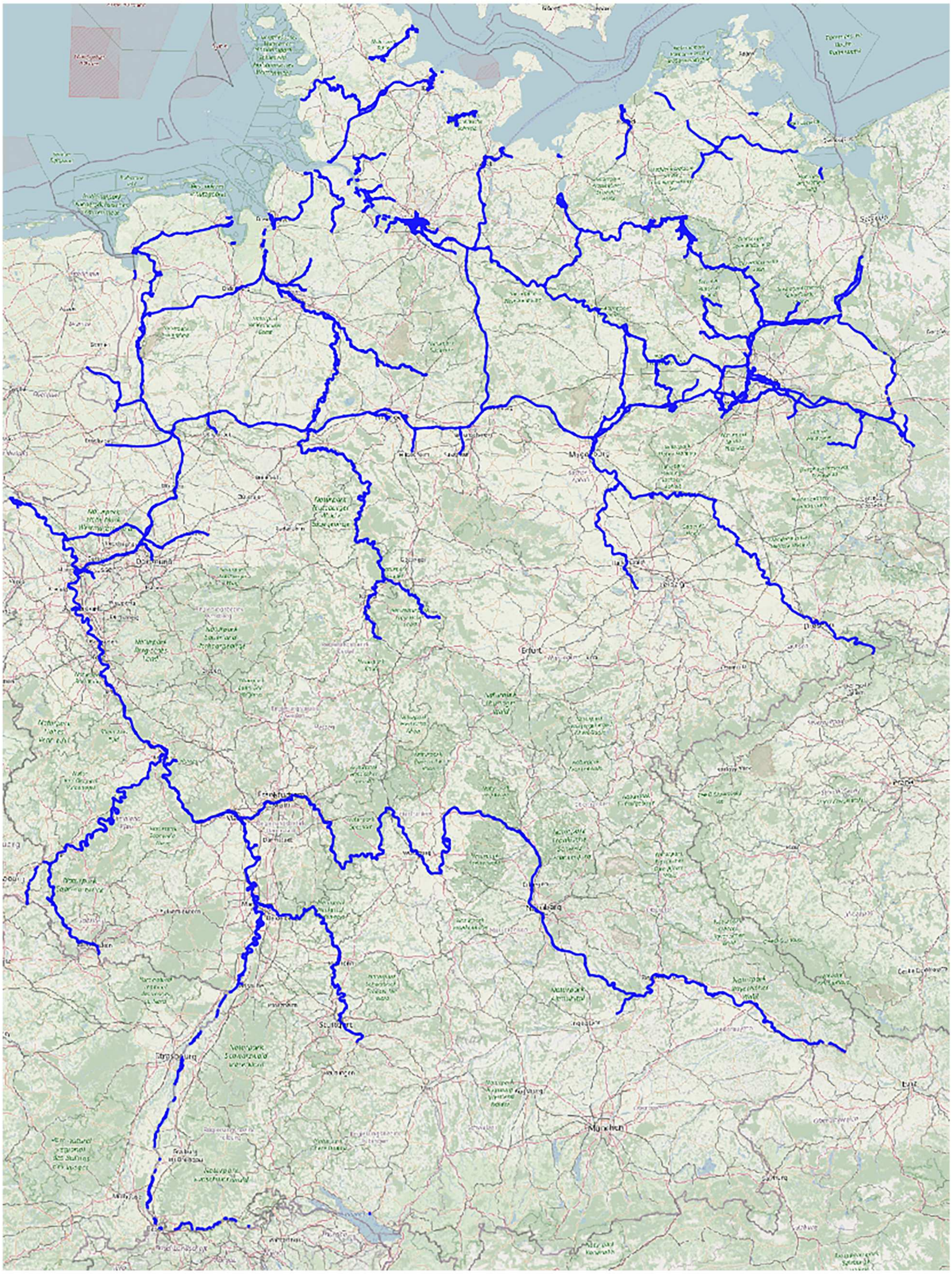

Figure 4. German inland waterway network (Map: © OpenStreetMap contributors, Data: © Rrg 2022).

will predominantly result in smaller batteries, which therefore have a better potential to be deployed in the retrofitting of existing vessels.

In the second case (case 2), the battery capacity is doubled, which allows for the rated power to be supplied for a period of two hours. Nevertheless, the

Table 1. Makeup of the considered fleet in terms of types assigned by Clarksons Research (2024).

	Passenger	Cruise	Dry Cargo Small (≤80 m)	Dry Cargo Medium (80–110 m)	Dry Cargo Large (≥110 m)	Liquid Cargo Small (≤80 m)	Liquid Cargo Medium (80–110 m)	Liquid Cargo Large (≥110 m)	Others
Vessel Count	104	218	189	777	317	104	460	327	39
Tank-to-wake CO2 Emissions on considered tracks [kt]	7.02	41.04	13.13	133.34	97.25	5.93	104.24	100.55	2.41

maximum battery capacity under consideration remains at 8 MWh.

Another significant assumption is that of the length of time that is necessary for the battery system to be recharged. Case 1 and case 2 assume that a minimum stop length of 10 minutes is necessary for the vessels to charge. However, this would be feasible only if an automated system were installed or if sufficient personnel were available at each charging station to enable other tasks, such as unloading, to be carried out simultaneously. Alternatively, the vessels could charge during longer stops or overnight. Consequently in case 3, the minimum stop length has been increased to 1 hour, while the battery sizes remain the same as in case 1. An overview of the input parameters for the different cases can be found in Table 2. The potential for hybrid diesel electric propulsion systems in each of the considered cases can be derived from Figure 5. It can be observed that, in line with the assumptions made in case 1, the achievable median share of battery electric propulsion relative to each vessel's total energy demand is 47.5%, while the upper quartile is 73.0%. Exactly 100 vessels may even be able to achieve fully electric propulsion with the small batteries considered in case 1. Most of these ships are either passenger vessels or small tankers and would require a battery capacity of less than 1 MW for full electrification of their propulsion systems.

Grouping the vessels by type shows that passenger and small liquid cargo vessels (except for those for which no type has been assigned) have the highest potential for battery electric propulsion. The median value for those groups is 96%. 35% of passenger vessels can be fully electrified. The probable cause is the predictability of the vessels' routes, which feature frequent stops that can be utilized for recharging the vessel. This is particularly the case with river crossing ferries, which typically have relatively short voyages. If the time for loading and unloading is sufficient, these stops can simultaneously be used for topping up the battery. Similarly, small liquid cargo ships are often ship to ship bunker boats for other IWW vessels, which also feature short operational times with frequent returns to shore. River Cruise ships show good potentials too, with the median value reaching 70%. It must however be noted that the auxiliary power is not considered here. Some cruise ships may have significant hotel loads, which introduce additional energy demands not accounted for in the current analysis and may require further energy management systems. Dry Cargo vessels achieve slightly higher battery electric shares than liquid cargo vessels. In general it can be observed that the smaller the vessel, the higher the potential for hybrid propulsion systems. These differences are especially pronounced for vessels with an LOA below 80 m.

Table 2. Input parameters for the considered calculation scenarios.

	Case 1	Case 2	Case 3
Maximum Operating Time at Rated Power [h]	1	2	1
Minimum Charging Time [min]	10	10	60

Doubling the battery capacities could increase the median battery electric share to 69.7% with the upper quartile reaching over 90%. The significance of the installed battery capacity is especially pronounced, when looking at the cargo vessels (dry and liquid). The median battery electric share of the vessels in all of these categories (except for small liquid cargo ships) increase by more than 20%.

As expected, increasing the minimum stop length required for charging reduces the proportion of the total energy consumption that can be supplied by batteries. For the considered fleet, the median battery electric share decreases to 34.8%. One possible explanation for the pronounced decrease in battery electric propulsion in case 3, is that stops in water locks can no longer serve as charging stops. In most cases these stops last between 15 to 30 minutes, which would not be sufficient for charging anymore.

The total potential for tank-to-wake CO_2 emission savings on the analysed tracks are 35%, 52% and 26% for cases 1, 2 and 3 respectively. Hybrid battery electric propulsion could therefore already make a significant short term contribution towards reducing emissions for IWW transport in Germany. Moreover, IWW vessels would have a reduced impact on air pollution, which is of particular significance in the densely populated Rhine region, where the majority of IWW traffic is concentrated.

As can be derived from Figure 6, the required battery capacities to achieve these savings predominantly fall within the range of 1 to 2 MWh for case 1. As discussed earlier, this is achievable with a state of the art 20 ft Container battery system. With a C-rate of 3, as considered here, this would result in chargers with a power between 3 and 6 MW. Such a configuration

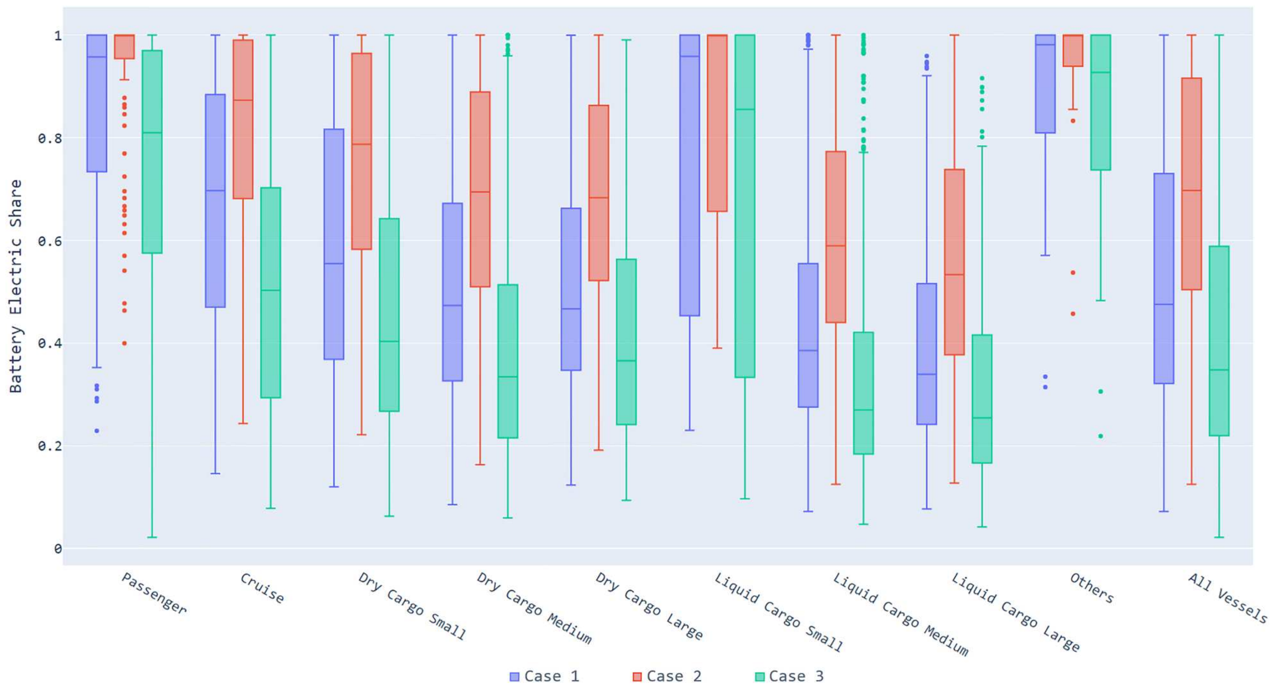

Figure 5. Potential for hybrid battery electric propulsion.

would place a significant burden on the electrical grid and is likely achievable only in a limited number of locations at present. The next section will therefore analyse the minimum necessary charger power to achieve the electrification potentials calculated in this section.

3.2. Optimizing the charger power

To reduce the burden on the electrical grid, smaller chargers are favourable to larger ones. Moreover, a complete network of chargers would require their installation in more remote areas, where the required grid infrastructure to support charging stations in the multi-megawatt range is likely unavailable. In relation to this, the model outlined in Section 2.2.2 can be applied to minimize the maximum requisite charging power for the realization of the electrification potentials calculated in Section 3.1.

Figure 7 presents the results as calculated by the model for the three different cases considered before. As anticipated, the larger the potential for electrification, the larger the charger size that is required. For case 1, the vast majority of the necessary charger power falls below 200 W. This power range is already achievable with state of the art fast chargers for electric cars. In case 2, approximately 75% of the vessels could still be supplied with chargers smaller than 200 kW and two thirds with chargers below 300 kW. The extended minimal stop lengths for charging in case 3 allow for even lower charging power, with 90% of vessels recharging below 100 kW. From the results it can overall be concluded, that there is considerable potential for hybrid propulsion systems for vessels sailing on the German IWW network. In order to achieve this, the requisite charger power is not significantly higher than that which is currently available on the market for electric road vehicles. It could thus be feasible to consider the installation of intermodal charging stations that could be used by both IWW vessels and road vehicles, provided that the location is suitable for serving both types of customer. Furthermore, this would mitigate the economic risk for potential investors in a charging infrastructure network, as it would provide a more diverse customer base. Nevertheless, further investigation is needed to identify potential limitations and determine the optimal locations for installing such chargers.

3.3. Potential for fully electric propulsion system

As is apparent from the results outlined in the previous sections, hybrid propulsion systems already have the potential to reduce the environmental impact of the analysed IWW fleet by a significant amount. However in order to further enhance the environmental footprint, a complete renunciation of fossil fuels is necessary in the long run. The requisite charging power and battery capacities for fully electrifying the considered fleet are therefore derived in accordance with the model adjustments outlined in Section 2.2.3. Figure 8 illustrates the technological requirements for fully electric propulsion systems for the specified fleet of IWW vessels. Each dot represents one vessel, while the diamonds are the median values for the different ship types. The x-axis depicts the requisite battery capacity, while the y-axis displays the minimum charging power as calculated by the optimization model. Both

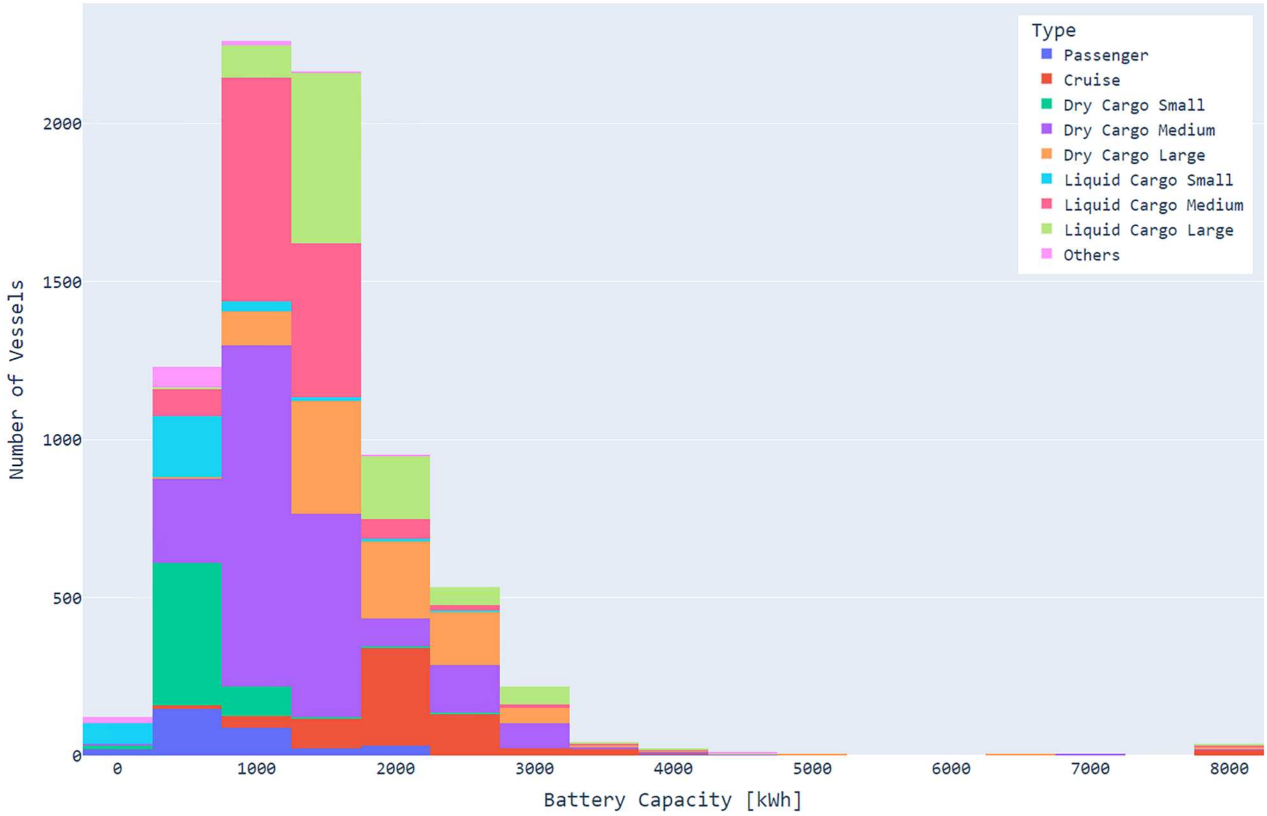

Figure 6. Necessary battery capacities for the share of electric propulsion calculated in case 1.

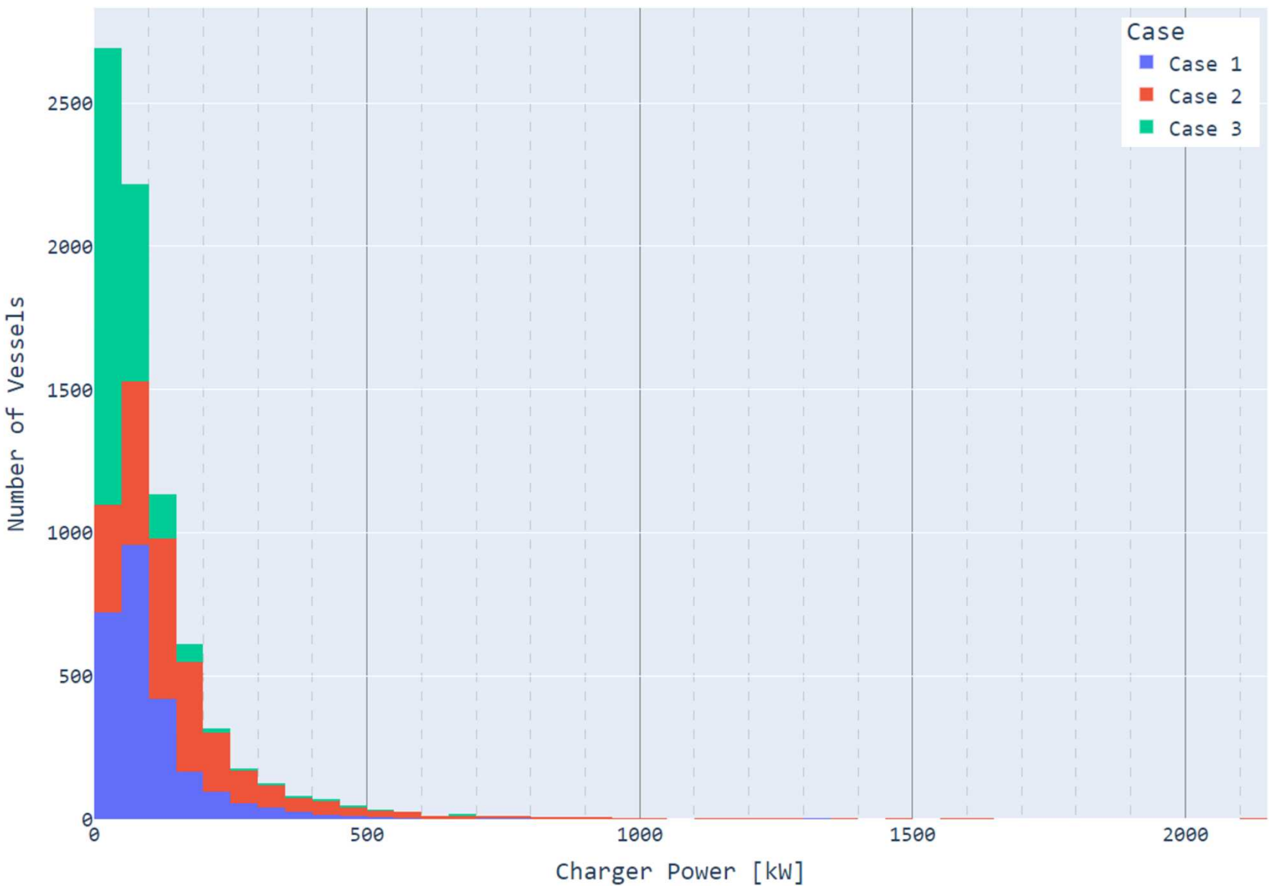

Figure 7. Minimum charger power required to reach battery electric share from Figure 5.

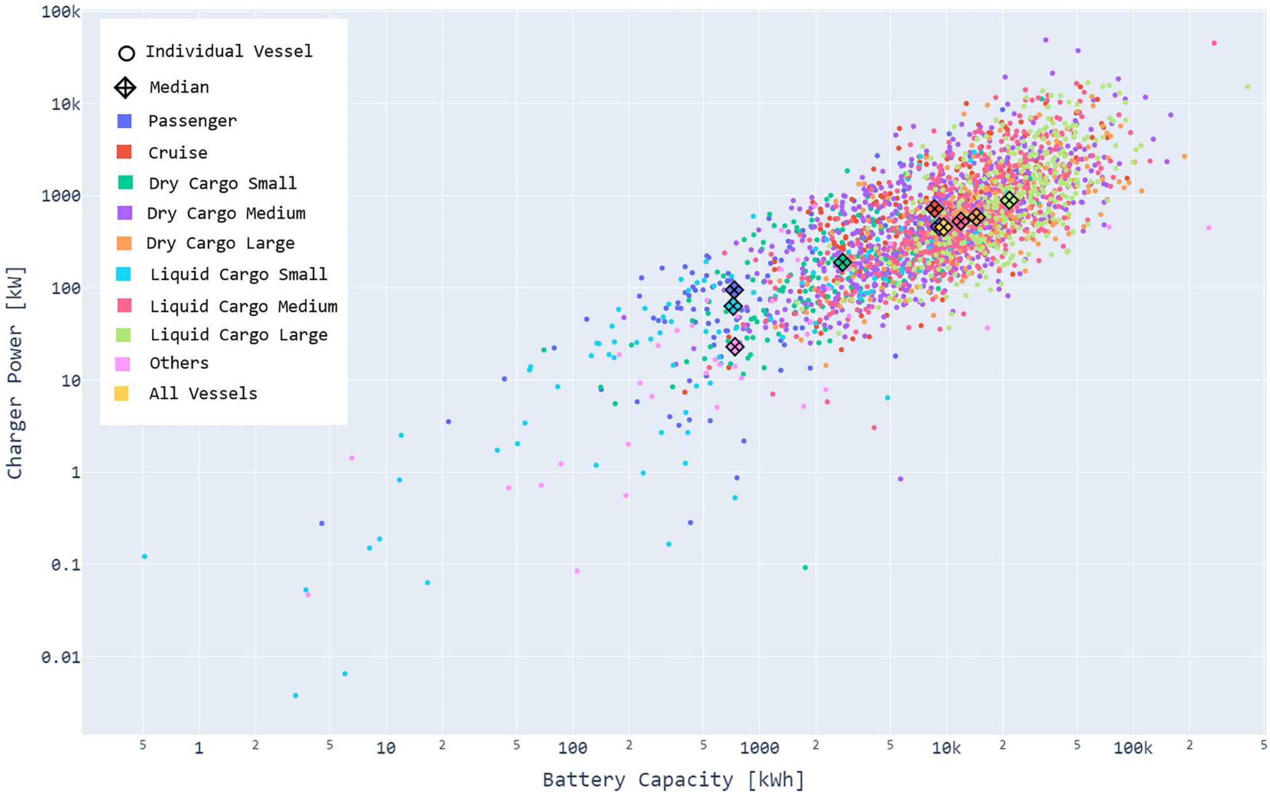

Figure 8. Necessary battery capacities and charging power for fully electric propulsion systems.

axes are presented on a logarithmic scale. The median IWW ship, would have to install a battery of 9.66 MWh and would charge with a power of 454 kW. Assuming the same maximum battery capacity of 8 MWh as before and a maximum charging power of 7.2 MW, which is equivalent to the charging power of the 'Bastø Electric' charging station for one of the largest electric ferries in the world (DNV 2021), the share of the entire fleet that could run on a fully electric propulsion system would be 42%. The requisite C-rates are below 1.5 in all cases and therefore already achievable with current technology.

When grouping the ships by type, it becomes apparent that, with the exception of vessels without an assigned type, passenger vessels and small tankers still display the highest potential for a fully electric propulsion system. This is likely due to their short operational times between frequent stops. Overall it can again be observed, that smaller vessel are easier to electrify as compared to larger vessels. The differing potentials are especially pronounced between the 'small' and 'medium' size segments. Large liquid cargo vessels are the most difficult group to electrify, with the median battery capacity exceeding 21 MWh.

As demonstrated by the data presented here, there are instances where vessels may require batteries of considerable capacity. This is due to some journeys being of substantial length, with insufficient opportunities for charging along the way. These journeys are frequently conducted on the Rhine, starting at Dutch coastal ports and reaching various destinations in the southern regions of North Rhine-Westphalia and Rhineland-Palatinate. In such instances, it may be necessary to make adjustments to the vessels' schedules in order to exclusively utilize a battery electric propulsion system for the larger vessels. This may, however, also present an opportunity to enhance the operational efficiency of IWW vessels in the long term, from both an environmental and an economic standpoint. Furthermore, a significant proportion of the IWW vessels currently in operation on the Rhine, were built in the 1960s and 1980s (Zentralkommission für die Rheinschifffahrt 2024). It may therefore be necessary to modernize the fleet in the near future. This could facilitate a more accelerated market penetration of alternative propulsion systems.

4. Discussion

In this paper, AIS data is used to calculate the potential for battery electric propulsion systems on IWW vessels. The methodology and findings of this study warrant further discussion.

The first and most important point to consider is the AIS data itself. As pointed out earlier, and as several other studies have shown, AIS data for IWW vessels can often have large gaps, which prevent a clear picture of vessel activity in these regions. This introduces an element of uncertainty when attempting to quantify the potential of battery electric propulsion systems for a specific fleet. In total 36.5% of the data had to be discarded due to lost targets within the tracks. While it is possible to fill these gaps, it is challenging to accurately recreate the exact operational profile, including the identification of berthing events in the correct locations. However, it is reasonable to assume that the missing operations would follow somewhat similar profiles to those suggested by the available data.

A further challenge for repairing the data is the lack of an emission reporting system for IWW ships, which could help to draw more accurate conclusions about the vessels activities during periods with 'lost targets'. Moreover, this renders the validation of the calculated energy demands and emissions an inherently challenging process. The methodologies employed in this study have been validated for a fleet of coastal and short-sea vessels, as well as by the IMO (2020). Nevertheless, a validation specifically for IWW vessels would be beneficial in order to enhance the reliability of the results.

Another point of discussion are the assumptions made about retrofitting existing IWW vessels. Here the volume of the propulsion system is considered to be the primary limiting factor. For IWW vessels, weight is also an important factor to take into account, especially in light of the anticipated increase in low water level events on the Rhine due to climate change. This also effects the energy demand of the vessel. Since batteries are heavier than traditional fuel tanks, the draft of the vessel will increase while its under-keel clearance will decrease. This leads to an increase in hull resistance and therefore energy demand (Mucha et al. 2017). This may also impact the accuracy of the energy demand model presented here. The installation of additional propulsion systems on board the vessel could therefore force operators to reduce cargo loads especially when water levels are low, which would represent an economic burden for the sector. Consequently, further investigation into the impact of reduced under-keel clearance in light of heavier propulsion systems and low water levels on potential retrofitting activities and energy demand models is warranted. Similarly, the effect of confined waterways on the energy demand should also be investigated. The added resistance due to the bank effect may be significant, especially for smaller canals (Zhang et al. 2023). As the majority of the observed traffic in this study is concentrated on the relatively wide Rhine, added resistance due to confinement are not further considered. However, for more accurate energy demand predictions, further studies on the effects and its integration into fleet-level energy demand models should be carried out.

More attention should also be given to the feasibility of installing chargers in the desired locations. The amortization period for the installation of charging facilities for IWW vessels could be considerable, particularly given the scarcity of customers during the networks build up phase. This creates a chicken and egg problem, which is difficult to resolve. The retrofits will only be carried out if vessel operators can expect a functional charging network, while the installation of the charging infrastructure requires customers to validate their installation. Wherever possible, intermodal charging stations, that are not exclusively limited to IWW vessels, may present an interesting market opportunity. As demonstrated, the charging power for both customer groups may fall within a similar range. Moreover, the impact on the electrical grid must also be accounted for. Careful planning is therefore essential to ensure the optimal distribution of investment, thereby facilitating the installation of an initial charging network. A further point for consideration is that the results presented here would necessitate the establishment of a substantial network of charging stations, resulting from frequent charging stops for the vessels. This is because the model developed here minimizes the maximum charging power rather than the total number of charging operations for each vessel. Since the build up of a charging network will take time, it is therefore crucial to identify the locations with the greatest potential to guarantee optimal coverage as soon as possible.

Battery swapping is another possibility to allow for faster replenishment cycles. Furthermore, this approach would facilitate the charging of batteries in a manner that is synchronous with the load on the electricity grid. This would help to prevent the grid from being overwhelmed by additional power demands during peak hours. However, sufficient space for energy containers on board the vessels as well as the establishment of an appropriate infrastructure to enable battery swapping operations would be necessary.

The primary focus of this study is at the fleets perspective. It should however be noted, that retrofitting vessels with battery electric or hybrid propulsion systems might not always be feasible. Some specific cases may prohibit the integration of a battery or a new drive train. In this case, shipping operators may look into new builds or different alternatives to reduce emissions from their operations. Future research should therefore look deeper into the issues associated with retrofitting vessels especially with regards to the long life time of ships.

5. Conclusion

This paper analysed the potential for electrical propulsion on the German IWW network. The overall energy demand and operational profile was assessed using AIS data from 2535 vessels. Based on this, the potential for battery electric propulsion systems was analysed. Three different assumption regarding battery sizes and minimum charging time were made to analyse the sensitivity of the results to those input parameters. Additionally, a linear programming model was developed to minimize the requisite charger power for a hybrid and for a fully electric propulsion system.

The results demonstrate considerable potential for electric propulsion systems on the German IWW. The hybrid diesel-electric propulsion system yielded median electrification potentials between 35% and 70% for the majority of vessels, with the battery capacities having the most significant impact on the results. The implementation of larger batteries has the potential to achieve tank-to-wake CO_2 emission savings of up to 52% for the analysed tracks, whereas the use of more modest battery capacities has been shown to result in savings of up to 35%.

The optimization of charging power for the hybrid diesel electric propulsion systems has resulted in chargers with a requisite power of a few hundred kW, which can already be supplied by fast chargers used for road vehicles. Consequently, the installation of the necessary infrastructure should already be feasible in most cases.

Although full electric propulsion may not be a viable option for the entire IWW fleet at this time, a notable proportion of vessels may already be suitable for operation solely on batteries. In particular, passenger ships and smaller tanker vessels exhibit considerable potential for electrification of their propulsion systems. However, for larger vessels, battery capacity and, to a lesser extent, charger power would necessitate significant technological advancement to enable the continuation of operations in the current form. As an alternative, operational profiles could be modified to permit the inclusion of additional charging stops. Furthermore, this could entail the consolidation and optimization of the current freight transport routes. In light of the age structure of the current fleet, it is likely that new builds will be required for a significant proportion of the existing fleet in the coming years. The introduction of a new, more efficient and sustainable method of transporting goods, encompassing not only the propulsion system but also the operational procedures themselves, may therefore be essential if the IWW network is to become more sustainable and if the sector is to remain competitive with road and rail transport.

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References

Anwar S, Zia MYI, Rashid M, de Rubens GZ, Enevoldsen P. 2020. Towards ferry electrification in the maritime sector. Energies. 13:6506. doi: 10.3390/en13246506

BDB. 2024. Das system wasserstraße. https://www.binnenschiff.de/system-wasserstrasse/wasserstrasse/. Zugriff am 31. Juli 2024.

BSR Electric. 2020. Electric ferries in the baltic sea region compendium. [accessed 2024 Oct 14]. https://www.bsr-electric.eu/content/5-use-cases/e-ferries/usecase7-finalreport.pdf.

Campillo J, Domínguez-Jimenez J, Cabrera J. 2019. Sustainable boat transportation throughout electrification of propulsion systems: challenges and opportunities. In: 2019 2nd Latin American Conference on Intelligent Transportation Systems (ITS LATAM). IEEE. p. 1–6.

Chatelier JM. 2023. Entering a new era for electrical vessel on inland waterways. Ship Sci Technol. 16:21–32.

Clarksons Research. 2024. Clarksons world fleet register. https://www.clarksons.net/wfr/.

Corvus Energy. 2023. Corvus bob containerized battery room. https://corvusenergy.com/products/energy-storage-solutions/corvus-bob-container/.

DNV. 2021. Charging into tomorrow today. https://www.dnv.com/expert-story/maritime-impact/Charging-into-tomorrow-today/.

ES-TRIN. 2023. European standard laying down technical requirements for inland navigation vessels (ES-TRIN). https://www.cesni.eu/wp-content/uploads/2022/11/ES-TRIN23_signed_en.pdf.

European Commission. 2016. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions – a European strategy for low-emission mobility. [accessed 2024 Oct 14]. https://eur-lex.europa.eu/resource.html?uri=cellar:e44d3c21-531e-11e6-89bd-01aa75ed71a1.0002.02/DOC_1&format=PDF.

European Environment Agency. 2024. Specific CO2 emissions per tonne-km and per mode of transport in Europe. [accessed 2024 Oct 14]. https://www.eea.europa.eu/en/analysis/maps-and-charts/specific-co2-emissions-per-tonne-2.

Eurostat. 2023. Répartition modale du transport intérieur de fret.

Fan A, Wang J, He Y, Perčić M, Vladimir N, Yang L. 2021. Decarbonising inland ship power system: alternative solution and assessment method. Energy. 226:120266. doi: 10.1016/j.energy.2021.120266

Fujii M, Yamashita K, Urakami M, Wakabayashi N. 2014. The study of simple navigation system for small craft using Class B AIS. In: OCEANS 2014-TAIPEI. IEEE. p. 1–4.

Future Proof Shipping. 2024. Future proof shipping. [accessed 2024 Aug 7]. https://futureproofshipping.com/.

Ghimire P, Zadeh M, Pedersen E, Thorstensen J. 2021. Dynamic efficiency modeling of a marine dc hybrid power system. In: 2021 IEEE Applied Power Electronics Conference and Exposition (APEC). IEEE. p. 855–862.
Haase O, Apenbrink S, Krebs SR, Segieth P, Holbach G. 2020. Design and system integration of a hybrid inland push boat powered by hydrogen fuel cells and li-ion nmc batteries and the challenge of providing a bunkering infrastructure. Ship Technol Res. 67:61–68. doi: 10.1080/09377255.2018.1523979
Hagemann S, Dümenil L. 1997. A parametrization of the lateral waterflow for the global scale. Clim Dyn. 14:17–31. doi: 10.1007/s003820050205
Hagemann S, Stacke T, Ho-Hagemann HT. 2020. High resolution discharge simulations over europe and the baltic sea catchment. Front Earth Sci. 8:12. doi: 10.3389/feart.2020.00012
IMO. 2020. Fourth imo greenhouse gas study 2020. International Maritime Organization. Tech. Rep. https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx.
Jiang H, Peng D, Wang Y, Fu M. 2021. Comparison of inland ship emission results from a real-world test and an ais-based model. Atmosphere. 12:1611. doi: 10.3390/atmos12121611
Karkosiński D, Rosiński WA, Deinrych P, Potrykus S. 2021. Onboard energy storage and power management systems for all-electric cargo vessel concept. Energies. 14:1048. doi: 10.3390/en14041048
Kelderman B, Friedhoff B, Guesnet T, Holtmann B, Kaiser R, Markus E, Robert R, Dasburg N, Liere R, Quispel M, et al. 2016. Prominent – d1.1 list of operational profiles and fleet families. European Commission. Tech. Rep.
Kolodziejski M, Michalska-Pozoga I. 2023. Battery energy storage systems in ships' hybrid/electric propulsion systems. Energies. 16:1122. doi: 10.3390/en16031122
Krause S, Wurzler L, Mørkrid OE, Fjørtoft K, Psaraftis HN, Vilanova MR, Zis T, Coelho NF, van Tatenhove J, Raakjær J, et al. 2022. Development of an advanced, efficient and green intermodal system with autonomous inland and short sea shipping – aegis. J Phys: Conf Ser. 2311:012031. https://dx.doi.org/10.1088/1742-6596/2311/1/012031.
Litwin W, Leśniewski W, Piatek D, Niklas K. 2019. Experimental research on the energy efficiency of a parallel hybrid drive for an inland ship. Energies. 12:1675. doi: 10.3390/en12091675Available at https://www.mdpi.com/1996-1073/12/9/1675.
Mucha P, el Moctar O, Dettmann T, Tenzer M. 2017. Inland waterway ship test case for resistance and propulsion prediction in shallow water. Ship Technol Res. 64:106–113. doi: 10.1080/09377255.2017.1349723
Norris A. 2006. Automatic identification systems–the effects of class b on the use of class a systems. J Navig. 59:335–347. doi: 10.1017/S0373463306003766
Perčić M, Vladimir N, Fan A. 2020. Life-cycle cost assessment of alternative marine fuels to reduce the carbon footprint in short-sea shipping: a case study of croatia. Appl Energy. 279:115848. doi: 10.1016/j.apenergy.2020.115848
Prina MG, Zubaryeva A, Rotondo G, Grotto A, Sparber W. 2023. Optimal fleet transition modeling for sustainable inland waterways transport. Appl Sci. 13:9524. doi: 10.3390/app13179524
© Rrg. 2022. RRG Gis Database, Inland waterways, shipping routes and port data; Oldenburg in Holstein, Germany. www.brrg.de.
Sang Lz., Wall A, Mao Z, Yan Xp., Wang J. 2015. A novel method for restoring the trajectory of the inland waterway ship by using ais data. Ocean Eng. 110:183–194. doi: 10.1016/j.oceaneng.2015.10.021
Vilarinho A, Liboni LB, Cezarino LO, Micco JD, Mommens K, Macharis C. 2024. Challenges and opportunities for the development of inland waterway transport in Brazil. Sustainability. 16:2136. doi: 10.3390/su16052136
Wärtislä. 2024. Hybrid marine system – wärtsilä hy. https://www.wartsila.com/marine/products/ship-electrification-solutions/hybrid-solutions.
Yang S, Ma F, Sun H, Sun L. 2024. Optimal voyage scheduling of battery-swapping based inland all-electric ship fleet considering environmental factors and time-of-use electricity price. In: 2024 9th Asia Conference on Power and Electrical Engineering (ACPEE). IEEE. p. 1814–1822.
Zentralkommission für die Rheinschifffahrt. 2024. Jahresbericht 2024: Europäische binnenschifffahrt und marktbeobachtung. https://inland-navigation-market.org/wp-content/uploads/2024/10/CCNR_annual_report_DE_2024_WEB.pdf.
Zhang C, Ringsberg JW, Thies F. 2023. Development of a ship performance model for power estimation of inland waterway vessels. Ocean Eng. 287:115731. doi: 10.1016/j.oceaneng.2023.115731 Available at url-https://www.sciencedirect.com/science/article/pii/S0029801823021157.