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Use of supercapacitors for inland ferries in Germany based on empiric resistance calculations

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Abstract **To achieve the CO_2 reduction target, it is necessary to electrify the entire mobility sector, including inland waterway transport. For this reason, electrical ferries are being deployed around the world to decarbonize maritime transport. With their high energy density, lithium-based batteries are the dominant electrical energy storage (ESS). However, due to their inherent technological disadvantages with a comparatively slow charging rate and limited cycle life, their areas of application are limited. Therefore, the project aims to evaluate the potential of supercapacitors in ferries. Supercapacitors offer a high-power density with a long cycle life, making them a promising technology for ferries with a short charge time, high load power peaks or as part of a hybrid ESS during the acceleration phases of the ferry crossing. An empiric simulation of the German inland fleet is conducted to validate the application of supercapacitors.**

Keywords— ferry, supercapacitor, empiric ship resistance, load profile

I. Introduction

The impact of the maritime transportation greenhouse gas emission worldwide is estimated to be around 3 % of the global emissions and expected to rise to 15 % according to a study from the International Maritime Organization (IMO) [1, 2]. Therefor a reduction of the CO_2 emissions of 40 % by 2030 and 70 % by 2050 is set for the entire fleet, while the goal is to achieve net-zero in 2050 [3]. Although inland ferries fall under the regulation of their respective countries the goal should remain the same.

In Germany 113 inland passenger ferries and 161 car ferries with an installed power of 12,145 kW and 44,935 kW (in total 57 MW) in 2022 are listed [4]. With an average age of 39.9 years respectively 48.8 years most inland ferries are using a diesel engine to power the propulsion and passenger related systems. A study from 2022 regarding costal ferries listed 105 vessels in Germany (77 under German flag) with a total emission of approx. 309,000 t of CO_2 per year and an average age for the European fleet of 35 years [5]. As a result, laws have been passed to speed up the electrification of the ferries. For example, in Hamburg all motorboats and ferries must be equipped with emission-free motors by 2030 to be allowed to run on the Alster [6].

Supercapacitors (SC) are already widely discussed for peak shaving and recuperation in electric cars and busses where they are used to support acceleration and braking [7, 8]. With an energy density of 1 – 10 Wh/kg and a power density of several kW/kg supercapacitors are highly suitable for hybrid energy storage systems (HESS) in onshore vehicles. As maritime vehicles have different power profiles and driving dynamics, the application of SCs is a current subject of research [9-11].

Up to this date only two ferries have been completely equipped with supercapacitors: the Ar Vag Tredan [12] and the New Ecology [13]. The French ferry was decommissioned in 2019 due to technical issues and currently retrofitted with batteries to be launched again in 2026 [14] while the current status of the Chinese ferry is not public.

This study aims to identify the potential for the electrification of the German inland ferry fleet using supercapacitors based on publicly available data.

The paper starts with an analysis of energy storage systems with requirements for HESS for ferries and shore-side HESS for grid-serving purposes. Afterwards the energy consumption for the German inland ferry fleet is conducted by acquiring available data, developing speed profiles and calculation with different empiric ship resistance methods. Finally, the paper concludes with the result that superconductors ESS are feasible for the German fleet with only a few exceptions and with recommendations for future developments in the field of ESS and the demand of new empiric ship resistance for shallow waters.

II. Energy storage systems for inland ferries

A. Energy storage analysis

As the energy density of electric storage systems (EES) is significantly lower than their fossil counterparts, the decision for the optimal technology depends on the scope of application.

An important aspect in developing electric operated ferries is to implement a suitable storage system for the specific task [15]. In a study from the European Maritime Safety Agency (EMSA) 16 commercial and 13 future ESS were rated for their possible application in the maritime sector [16]. The most applicable for the use in ships were *Nickel manganese cobalt oxide* (NMC), *Lithium iron phosphate* (LFP), *Nickel Cobalt Aluminum* (NCA) and *Lithium Titanate Oxide* (LTO) with mentioning supercapacitors as suitable for low-energy peak shaving.

For Ferries LTO is the preferable battery choice as this chemistry has a high cycle life, fast charging capabilities and durability [15]. The relatively high specific cost per capacity on the other hand is a disadvantage [15, 17]. Compared to the charging rate of the supercapacitors, which can be fully charged in under a minute, the C-rate of LTO with 4.3, which equals to a full-charge cycle in around 14 minutes, is comparable low and results in a deficit for many inland ferries.

Further important properties are the calendar life, usability as a second life ESS for the shore-side charging station, operation temperature range, the investment cost, safety requirements, and overall sustainability evaluated in a life-cycle assessment (LCA). These aspects need specific knowledge of the individual application and should be conducted as such. Compared to batteries supercapacitors have a regulation gap that hinders their market entry [18].

B. HESS Requirements for ferries

Both inland and coastal ferries offer possibilities for the implementation of supercapacitors as a part of a HESS. Inland ferries often operate between two destinations with a fixed schedule, high frequency, relatively small energy consumption and a very short time span to recharge the electrical storage. ESS only based on batteries are facing the issue of low recharge rates, which are typically between 0,25 h and 2 h, and a cycle lifetime from 5000 up to 7000 full cycles. An inland short-distance ferry has a typical lifetime of over 30 years with over 100.000 crossings resulting in numerous replacements of a battery only ESS.

In comparison, coastal ferries have longer crossing times, higher energy consumption per crossing and more time to recharge the electrical storage. These differences make batteries or fuel cells with a high energy density more suitable than supercapacitors. In this case, supercapacitors can be used to support the main ESS with peak shaving during high load phases for example while the ferry is maneuvering in the port. In the project “V-Access” the load profile is divided in a high energy and a high-power profile using a low-pass filter [17]. With this approach the ESS can be optimized for a high-energy ESS and a high-power ESS separately resulting in a smaller HESS overall.

C. Grid-serving charging of ferries

Similar to electric cars, the charging of E-ferries has to be done without violating the grid directives of the middle or low voltage grid. Especially for ferries in rural areas this can lead to significant obstacles in the implementation, if no further adjustments are considered [19]. Demand-Side-Management (DSM) is only a feasible option for certain time slots of ferry schedules, as it results in lower charge rates and can affect the crossing capability of the vessel. The over scaling of the HESS of the ferry is not a practical solution as the weight and/or volume is limited.

Hence, an additional onshore HESS is often installed to reduce the stress of the grid. To optimize costs, the onshore HESS can be combined with renewable energies (photovoltaic and wind energy) to decrease the size and costs of the storage and also decrease the costs of investments in the local grid. The costs of the shore-side HESS with a photovoltaic power plant combined with the investment in the charging infrastructure can offer a decrease of the overall cost for ferries with multiple stops as every charging opportunity reduces the size of the HESS of the ferry and offers a greater flexibility of load distribution in the grid.

III. Calculation of the inland Ferry consumption in Germany

A. Data acquisition of the German inland ferry fleet

Although the information of all ferries in Germany is published anonymized by the administration the data is mostly inaccurate and, in several cases, incomplete or false [20]. In addition to this obstacle, detailed knowledge about the ship dimensions and hull form or a test of a model of the ship in a towing tank is needed for an accurate calculation of the ship resistance. Inland Ro-Ro-ferries can differ significantly from the usual given parameter length-overall as the ramps on both sides of the ship can increase the length by over 20 % while not being relevant to the resistance calculation. First the false data had to be identified, for example if the volume of the ferry based on the multiplication length, width and depth were greater than the displacement volume and corrected. Secondly missing or unusual data had to be corrected using characteristic coefficient values for ferries [21, 22]. The third and last step was to balance corrected values evenly on the depended values. For example, if the block coefficient c_B is corrected which is defined as the ratio between the displacement volume and the block volume, the deviation is evenly proportional distributed on all values to reduce the statistical error in the calculation. After these corrections steps 239 of 274 ferries were useable for further calculation.

B. Speed profiles

Speed profiles of inland ferries mostly have a typical trapezoidal shape with a linear acceleration and deceleration phase. The maximum energy consumption occurs mostly during the steady-state crossing part of the journey while the highest load appears during the acceleration part. For inland ferries with a short crossing, e.g. few hundred meters, the speed profile can change similar to an exponential function without a plateau [23]. In this case the maximum energy consumption can also happen during the acceleration.

Double-ended inland ferries with two destinations usually do not show high power peaks caused by maneuvering in the harbor compared to ferry types with only one exit. Efficient mooring locations directly on the opposite side of the river are essential for reduced daily energy consumption.

C. Empiric calculation of ship resistance

Several different methods are known in the literature for the empirical calculation of ship resistance R_T (for a comprehensive overview refer to [22]). The ships resistance is a complex problem to calculate consisting mostly of the frictional and residual resistance depending not only on the ship's hull form and speed but also of the water conditions (waves, shallow water) [24]. As a result, each method is specific to certain type of ship and field of application (inland, coastal). An approach to reduce the deviation from the true value is to use multiple methods to calculate a mean resistance value [22]. For inland ferries and combination of Holtrop-Mennen [22], Zwankow [25] and the Leningrad Design-Office-Method [25] showed better results compared to Hollenbach [22], Guldhammer-Harvald [22], Van Oortsmerssen-Helmore [26] and Wróblewska-Sirotina [25].

D. Energy-saving operating profiles

The main disadvantage of supercapacitors is the low energy-density compared to state-of-the-art battery technologies which limit their use to short-distance inland ferries routes. To expand the field of application the power load profile of the ship must be as energy efficient as possible. As the amount of energy saving is mainly dependent on the maximum speed of the vessel during the trip because the propulsion power is exponentially connected to the speed (Formula 1 and Fig. I).

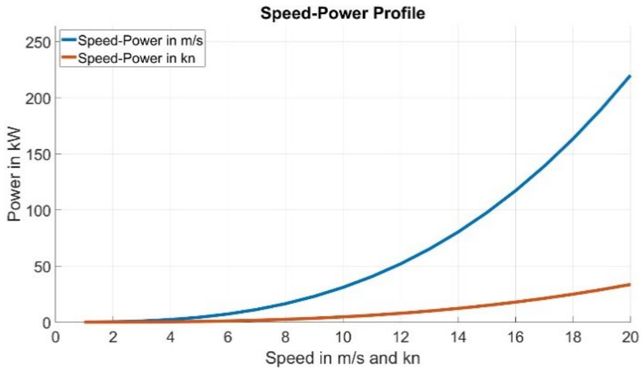

FIG. I EXAMPLE SPEED-POWER CURVE OF A FERRY

$$P_{load} = \mathrm{R}_T \cdot v^3 \cdot \eta \quad (1)$$

To calculate the power load of the ferry P_{load} the overall specific ship resistance R_T, the ship speed v and the efficiency of the propulsion η is necessary. With this simplified formula it is possible to extrapolate generic load profiles for each vessel and optimize for energy savings while keeping the same transportation profile by reducing the berthing time. [27] shows that the most efficient speed-profile is achieved by minimizing the maximum speed and acceleration as both are exponentially connected to POWER consumption. A gliding phase during which the thruster propulsion is zero offers less benefit than a lower maximum speed at the same total crossing time.

E. Calculation of the German ferry fleet energy consumption

With the public data gathered and the empirical calculation methods the resistance of each ferry can be approximated. For the electrical retrofit of the ferries several assumptions need to be made:

- Shipboard system efficiency $\eta_b = 0{,}85$
- Ship propulsion efficiency $\eta_p = 0{,}6$
- Max. ESS weight = 80 % of ship's deadweight
- Ship lifetime = 20 years
- Long berthing = 10 min berthing, 8 min charging
- Short berthing = 2 min berthing, 1 min charging
- Operation period = 6 AM to 10 PM, all seasons

	300 m	600 m	900 m	1200 m	1500 m	1800 m	2100 m	2400 m	2700 m	3000 m
1 m/s	0,92	1,06	1,22	1,35	1,52	1,65	1,81	1,95	2,13	2,23
2 m/s	0,85	0,92	0,99	1,06	1,13	1,22	1,28	1,35	1,44	1,52
3 m/s	0,82	0,87	0,92	0,97	1,02	1,06	1,11	1,16	1,22	1,26
4 m/s	0,81	0,85	0,88	0,92	0,96	1,00	1,03	1,06	1,10	1,15
5 m/s	0,80	0,83	0,86	0,89	0,92	0,95	0,98	1,01	1,04	1,06

FIGURE III: COST COMPARISON FOR SUPERCAPACITORS/LTO-BATTERIES FOR LONG BREAK TIME FOR DIFFERENT SPEEDS AND DISTANCES

	300 m	600 m	900 m	1200 m	1500 m	1800 m	2100 m	2400 m	2700 m	3000 m
1 m/s	0,58	0,83	0,98	1,11	1,26	1,41	1,56	1,70	1,88	2,04
2 m/s	0,37	0,58	0,76	0,83	0,90	0,98	1,05	1,13	1,20	1,28
3 m/s	0,31	0,44	0,58	0,72	0,78	0,83	0,88	0,93	0,98	1,03
4 m/s	0,28	0,38	0,48	0,58	0,69	0,76	0,80	0,83	0,87	0,91
5 m/s	0,26	0,34	0,43	0,51	0,59	0,67	0,75	0,78	0,80	0,83

FIGURE I: COST COMPARISON FOR SUPERCAPACITORS/LTO-BATTERIES FOR SHORT BREAK TIME FOR DIFFERENT SPEEDS AND DISTANCES

Two berthing options were chosen to highlight the influence of the charging time and the number of trips per day for the decision of the ESS. The short berthing time favors the high-power density of the supercapacitors whereas the longer berthing time the high energy density of the LTO battery. The amount of daily trip varies from 16 to 86 (long berthing time) to 18 to 299 (short berthing time) depending on crossing speed and distance.

An operation period 16 hours per day for all seasons is chosen as an example of a high-frequency year-round ferry. Lower frequency seasons (e.g. winter season) do not reduce the ESS size but have an impact on the electricity costs which is out of the scope for this paper. The reduction of energy density due to colder temperatures in the winter season is considered by the safety margins.

Characteristic	***LTO***	***Supercapacitor***
Gravimetric energy density in Wh/kg	100	3.5
Gravimetric power density in W/kg	100	4,180
Depth of discharge (DoD) in %	80	90
End of Life (EoL) in %	80	100*
Costs per capacity in €/kWh	700	20,000
Max. equivalent cycles	20,000	Up to 1,000,0000

Table I Characteristics for the comparison of LTO and SCs for inland ferries (*EoL-capacity of SCs set to 100 % due to high cycle life)

The characteristics for both ESS types are listed in Table I [15, 28]. The values for ship components are typical for ferries whereas the specifications of the supercapacitor are based on a commercially available component.

The simulations show that with the exception of only 13 at the highest speed, all inland ferries of the catalogue can be fully powered with supercapacitors without reducing the crossing speed or violating the maximum weight limit of the ESS. If the maximum speed is reduced to 4 m/s all the ferries can be retrofitted with supercapacitors.

The cost comparison (Fig. II and III) shows the relative cost savings between an ESS based on LTO-batteries and supercapacitors for all 239 ferries. The relation is cost of SCs to cost of batteries so that for values below 1 supercapacitors are the more cost-effective option and vice versa. For short charging times the SC-solutions is up to four times cheaper than the state-of-the-art battery option. Even for the long charging use case supercapacitors are shown as a viable option for very short distances.

IV. CONCLUSION

Germany has a high potential to reduce the CO_2-emissions by electrifying the inland ferries. Most of the vessels are older than 30 years and use diesel engines. By developing operational profiles, the necessary energy consumption can be reduced and improve the usage of a supercapacitor ESS/HESS. With an empirical resistance calculation approach the scope of application for supercapacitors is determined. The result shows that with small adjustments of the ship maximum speed all of Germany's ferries can be electrified and fully equipped with supercapacitors. Especially for short distances at high speed with a high daily crossing frequency supercapacitor ESS show promising market potential.

For a broad implementation in the field the regulation gap has to be closed, and more field tests must prove the market readiness of the whole system. In the near future new developments or improvements of battery types and supercapacitors in the aspect of energy density, power density, cycle life and costs per capacity can significantly change the choice of the optimal ESS. A general approach for use cases with high energy or high power demand combined with an optimization of the ferry schedule based on passenger traffic is therefore recommended for future studies as well as more in depth studies for empirical resistance methods for shallow water and short distance ferries.

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VI. Declaration Use of AI

I acknowledge the use of DeepL Translator and DeepL Write (https://www.deepl.com/de) to improve the writing of this publication. The final written text, analysis, and verification of original sources remain solely the responsibility of the authors.

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