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The necessity of time-based calculations for dimensioning of hybrid power supply systems of ships within the early design stage

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Abstract

While hybrid ship drive systems may offer a large potential, a thorough analysis is needed as it is strongly dependent on the operational profile. The fixing of costs during the early design stage, leads to the necessity of a precise evaluation of the systems efficiency within this phase. Conducting statistic-based calculations can be inadequate due to the time-dependent behavior of the battery. Moreover, idealized temporal data is often utilized for the design of battery supported ships. Therefore, this paper discusses the consequential inaccuracies using statistical or smoothed data. But also examines the potential of an advanced in-house developed statistical approach. For the examination, an internal developed method for dimensioning hybrid ship power systems is used. The paper shows that conducting statistical calculations lead to incorrect modeling of battery behavior, while smoothed power time-series can result in an overestimation of the battery lifetime (up to 21% less charge cycles).

Keywords

Fuel consumption, modeling hybrid energy system, ship energy efficiency, battery, ship design

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Introduction

Even though ships have a high environmentally friendly transport performance, they make a decisive contribution to climate change.[1] To support the energy transition, the International Maritime Organization (IMO) set the target to reduce greenhouse gas emissions from shipping by 50% until 2050 compared to 2008.[2] Beyond that, ships contribute to the local air pollution in ports. Optimizing shipping routes, speed reduction, energy efficiency, shore power supply and development of CO_2-neutral fuels are various approaches of the IMO to tackle the emission reduction. Due to low profitability and limited availability of CO_2-neutral fuels,[3] increasing efficiency in operation is an important issue. The high efficiency of conventional ships drive systems confines mostly to selected design conditions. However, despite higher transmission losses, hybrid drive systems can increase the efficiency in part load operation. Reason is the adaptability of the system to the operational profile. The battery can provide or store the needed power to operate the engine most efficient. Further efficiency gains are due to the possibilities of load leveling and peak shaving or providing back-up power.[4] Additionally, because of the possibility to store energy, ships can be operated temporary without emissions. A battery supported systems is especially beneficial, when the ship is subjected to a broad load spectrum. The efficiency increase depends highly on the considered operational profile. Therefore, knowing and using the appropriate data basis for designing the

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system configuration is crucial. In recent years a lot of work was done concerning operation-based ship design and considering the off-design performance of conventional ships. An example of such a method is given by Eljardt,[5] which was applied by Greitsch[6] for rudder designs and was improved by Krüger et al.[7] Within this method the operational profile is defined by different cumulative density functions for environmental influences (e.g. wind or current) and for ship conditions (e.g. speed or floating condition). For the evaluation of the vessel performance within the operational profile, a specific operational condition is generated using a Monte-Carlo approach. This condition is then analyzed in a force based maneuvering simulation (see Söding[8] and Krüger et al.[9]). By analyzing numerous operational conditions within the Monte-Carlo simulation, the full operational profile of the vessel is reproduced. For hybrid energy systems statistical input data can be inadequate due to the dynamic behavior of the energy storage systems. Especially the state of charge of a battery is dependent on previous time steps. Time series of the required power are often not or only simplified available. Therefore, this paper applies a new developed advanced statistic-based approach, which is compared to a calculation in time domain. Finally, its potentials and possible problems for a new hybrid ship designs are discussed. Furthermore, inaccuracies using simplified or idealized times series are examined. All of this is conducted with measured data from a diesel-electric double ended ferry and a calculation method for dimensioning hybrid drive systems. As hybrid drive systems can be composed in different manners, this paper concentrates on a ship designated for electrical propulsion and hybrid energy supply. In summary, this paper answers

- how a statistical data basis copes with the dynamic behavior of hybrid drive systems and
- how crucial high-resolution time series of the propulsion power is for the dimensioning.

Section 2 gives an overview on typical databases used for designing battery supported ships. In Section 3 the used calculation method and the data input approach is described. Next, Section 4 gives details about the ships task and the measured data. Finally, in Section 5 the results of the calculation and the influences of the different data inputs are shown, whereas Section 6 resumes the discussed topic.

Review of typical data input characteristics

To obtain an overview, this section covers typical types of input data used in literature for designing battery supported energy systems for ships. Those can be structured in statistical approaches and idealized time series with or without load fluctuations. Georgescu et al.[10] even investigates in assessing hybrid ship drive systems before looking into the operational profile. It shows the benefits of energy storage decoupled from the operational profile. Nevertheless, it is also stated, that determining the optimal capacity of the battery a detailed operational profile is needed. Influences of time dependencies are not elaborated. For examining yachts van Loon and van Zon[11] created a statistical speed profile from AIS-Data of 35 ships gathered over about 4 years. From speed and engine load relation the engine load distribution is determined, which is used for fuel consumption estimation. This neglects the temporal succession of the loads. In Völker[12] exemplary power time series with constant power segments are utilized to evaluate hybrid ship drive systems for a harbor tug and a ferry crossing a river. For evaluating an offshore support vessel Wang et al.[13] simplifies measured power time series by smoothing small power variations. So, both are considering time dependencies, but do not take load variations into account. However, Mashayekh et al.[14] prepares an idealized power time series from a speed profile of a ferry gathered from ship tracking data. Furthermore, sinusoidal power variations are added to the profile to simulate load variations. Hence, the power time series has a recurring behavior without statistical or occasional load peaks. Ovrum and Bergh[15] explore the battery support for crane operations using given operation cycles and vary the duration of specific phases for a more realistic power demand. Here, the phases are randomly changed, but the required power follows a constant value. Generally, it is common to use idealized time series based on the ship route in industrial practice.

There are a lot of different approaches designing battery supported systems.[16–27] However, the quality of the results depend on the used data basis. Thus, knowing about inaccuracies arising from simplified data is of utmost importance.

Description of the underlying method

A calculation method was developed in-house to enable a sufficient modeling of a hybrid energy system with electrical propulsion for evaluating the efficiency of different energy storage capacities. This calculation method is used to answer the questions that have arisen and is described in detail in Emmersberger et al.[28] The aim of this calculation method is to produce acceptable results for dimensioning hybrid ship power systems, while using only basic and available input parameters. This enables the utilization in the early design stage, where the data availability is poor. The calculation can be done based on a time series (measured or idealized data) or a cumulative distribution function of the required power. This approach has following limitations. Models of the electric engines or the propellers are not included (see also the system boundaries of the method in Figure 1). As data of the ship operation is needed, the interaction between engine control and

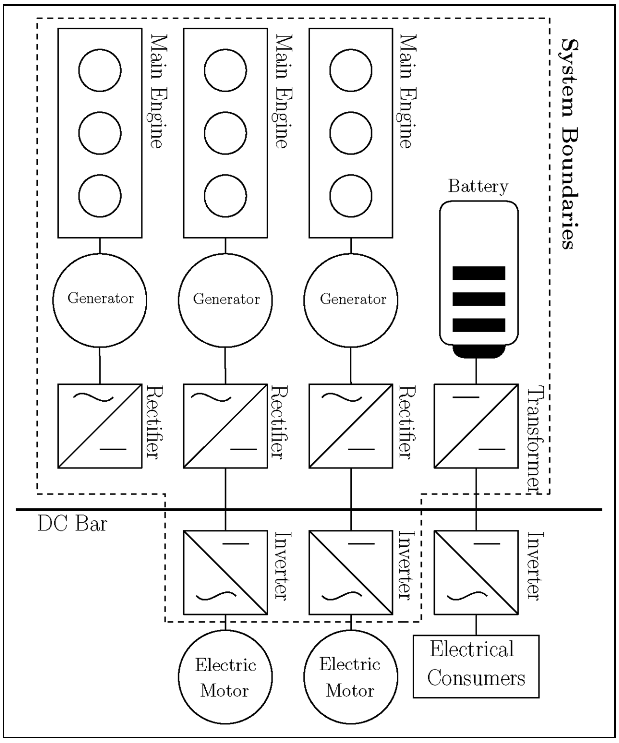

Figure 1. Schematic figure of the considered setup with the system boundary of the calculation method.

propulsion cannot be considered. Starting and stopping of the engine would lead to additional fuel consumption, which is not included due to lack of data. For every calculation point the power is split ideally onto the engines and battery for maximum efficiency.

Cost-relevant results are generated, such as fuel consumption, operational hours, and number of charge cycles. Sections 3.1 and 3.2 describes, how the input of the data is handled dependent on the type of data (time-based or statistical).

Input for time-dependent calculation

For the time-based examination the calculation method is fed with a time series of the required power with specific intervals (see Figure 2 as example). Every time step is evaluated regarding cost and system relevant parameter. The succession of the calculation points is relevant for calculating the state of charge of the battery. Also, the decision whether starting or stopping engines is dependent on previous event.

Input for statistic-based calculation

For using the statistic approach a cumulative distribution function (CDF) needs to be prepared. It can be achieved by applying the operation-based ship design mentioned in Section 1. For better comparison the CDF for this paper is created from the measured time series. By use of this distribution the Monte-Carlo Method is applied, where a uniformly distributed random number between 0 and 1 is drawn. With this number the function value (in this case the required power) of the distribution is determined and used as the input data for the calculation method. To reproduce the same time period, as many data points as used in the time series have to be drawn. Thus, both approaches get comparable. The amount of draws

$$n_{\mathrm{draws}} = \frac{T}{\Delta t} \tag{1}$$

is provided by the observed time period T and its interval Δt. The statistic-based calculation is performed without temporal connection. Therefore, no state of charge can be determined and the number of running engines is independent of the previous calculation point.

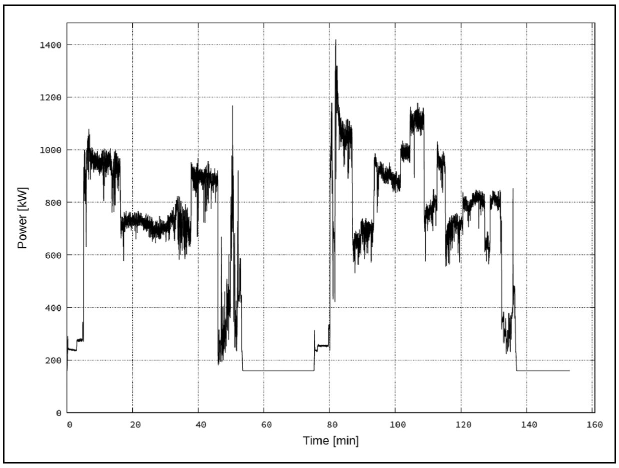

Figure 2. Excerpt of one round trip of the measured power.

Data basis

The measured data available for the examination originates from a diesel-electric double ended ferry. The main dimensions of the ferry are listed in Table 1. The vessel sails on a recurring route where one way takes about 30–60 min, while it stays in harbor between 15 and 30 min. The vessel accomplishes about nine trips per day and sails part of the time in restricted waterways with reduced velocity. On this data basis a new hybrid design was developed. To concentrate on the influence of the data-bases, the configuration is kept the same in this paper. The design process is described in Emmersberger et al.[28] It resulted in a configuration consisting of three engines with a power of 630 kW each and a battery system with a nominal capacity of 178.2 kWh with a recharge and charge power of 356.4 kW. The data set contains the needed power of the electric motors for every second and covers one and a half year. The hotel load was not recorded and is added as a constant to the required power. In Figure 2 an exemplary time series of the measured power for going back and forth is shown, whereas Figure 3 shows the cumulative distribution function based on data of 1 year. It must be noted, that the function is discontinuous at two points. The first jump is directly at a power of zero, which is due to the times when the ship is not in operation. The second jump is related to the base load of the electrical consumers. The simulation data is prepared with the Monte-Carlo approach (see Section 3.2). Figure 3 shows, that it is accurately overlapping with the distribution.

Influence of different data bases

This section investigates the impact of different databases on the calculation of a hybrid ship drive system. Section 5.1 discusses the difference between time-based and statistic-based calculation and Section 5.2 investigates the influence of load variations in the data.

Comparison of time-based and statistic-based calculation

The effect of having time-based and statistic-based databases is compared in this part. To make the approaches comparable, the time period and the time step of the calculation was set to 1 year and 1 s for both. Additionally, for a better examination the calculation was also done for a conventional energy system without battery. Section 5.1.1 shows the differences in the results of the calculation and Section 5.1.2 gives corresponding explanations and conclusions.

Table 1. Properties of the ship.

Breadth	about 13.50 m
Draft	about 1.80 m
Displacement	about 1400 t
Long. Center of buoyancy	36 m
Metacentric height	5 m
Speed	12 km

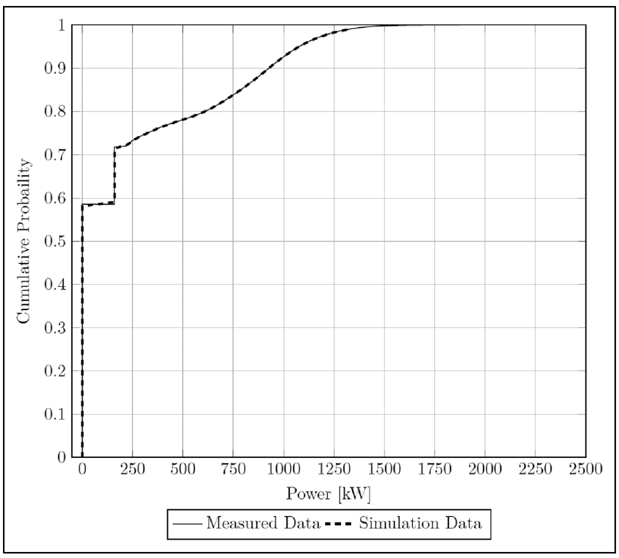

Figure 3. Cumulative distribution function for the calculation.

Comparison of the results. In Table 2, the different results of the calculation with statistical and time-based input data can be seen and the hybrid and the conventional (without battery) setups are compared. Comparing the setups, the time-based approach results in 2.1% less fuel consumption of the hybrid system, whereas the statistical approach determines an increase. Comparing the calculation approaches, the statistical approach obtains 2% less fuel consumption, 5% less load cycles, and 8% less operating hours of the engines. Furthermore, a difference between the charged and discharged energy is seen for the statistic-based calculation.

Discussion of the results. The main observations in the results are, that the statistic-based calculation

1. expects no efficiency gain in the hybrid drive system compared to the conventional system and
2. estimates a lesser overall fuel consumption compared to the time-based approach.

Reason for the first observation. To tackle this observation it needs to be looked into the fuel savings in line 2 of Table 2. The determining difference is, that for the statistical method the temporal succession is not known. Thus, the reason for point 1 is, that the state of charge of the battery is not tracked and for every calculation step the battery can be freely charged or discharged. Using the battery unevenly (e.g. more charging than discharging) leads to the imbalance between the charged and discharged energy that can be seen in the results. Calculating with chronological connection, the state of charge cannot exceed its upper and lower boundaries. This assures that the saved and used energy of the battery is equal assuming the same state of charge at the start and the end of the time period (see Table 2). It gets clearer, when calculating the potential fuel consumption for the additional saved energy 201.0 MWh – 149.1 MWh = 51.9 MWh by multiplying it with the average specific fuel oil consumption.

Table 2. Difference between the results of the time- and statistic-based calculation.

	Time-based		Statistic-based	
	Hybrid	Conv.	Hybrid	Conv.
Fuel consump. [t]	465.9	475.9	456.6	455.5
Fuel savings (%)	2.1		−0.2	
Load cycles	1029.6	-	975.9	-
Op. hours [h]	4724	5912	4346	5427
Charge [MWh]	186.9	-	201.0	-
Discharge [MWh]	186.9	-	149.1	-

$$51.9\text{MWh}\cdot\frac{210.7\frac{\text{g}}{\text{kWh}}}{1000}=10.9\text{t}. \quad (2)$$

By subtracting this error from the fuel consumption of the hybrid system (because it was saved too much energy), we get a corrected consumption of 445.7 t. This leads to a fuel reduction of 2.2% (instead of −0.2%) compared to the conventional drive system, which is nearly the same reduced fuel consumption determined in the time-based approach (2.1%). This shows, both approaches result in the same fuel savings, when the saved and used energy of the battery is in balance. Additionally, it appeared at first that the statistical approach reveals no profitability due to the imbalance. If the used energy is higher than the saved energy, it could also be the other way around, which gives a more misleading assessment.

Reason for the second observation. For this observation the overall fuel consumption in line 1 of Table 2 is of interest. The fact that the statistical approach leads to less fuel consumption is also the consequence of the missing order of events. Dynamic behavior like the starting and stopping of engines cannot be applied. The delay in the system control leads to inefficient engine loads in the time-based calculation. For instance, when the load drops temporarily, causing the engine to operate in part load, but the duration of the drop is too short to justify altering the amount of running engines. This can be illustrated in the load histogram of the engines (see Figure 4). In the statistic-based calculation (dotted) the engine load stays inside the predefined efficiency range (65%–90% MCR) and consequently leads to a better overall fuel consumption. Whereas in the other approach (shaded) the engine is also operated in part loads and a higher total fuel consumption occurs. Furthermore, because of the delayed cut-off mechanism, engines are temporarily longer in operation than necessary. This also explains the higher operating hours in Table 2.

Concluding remarks. The introduced statistic-based calculation can give estimations for economical relevant parameter like operating hours and charge cycles. When the distribution is resolved high enough, the influence of load leveling and peak shaving should also be included. Having only the operating mode and the corresponding time percentage, this is not the case. But for the use of a statistical approach following considerations should be taken into account:

1. It must be examined, if the saved and use energy of the battery is balanced. Otherwise, the prediction of the efficiency gain could be incorrect.
2. The missing temporal succession neglects dynamic events and leads to an underestimation of the overall fuel consumption.

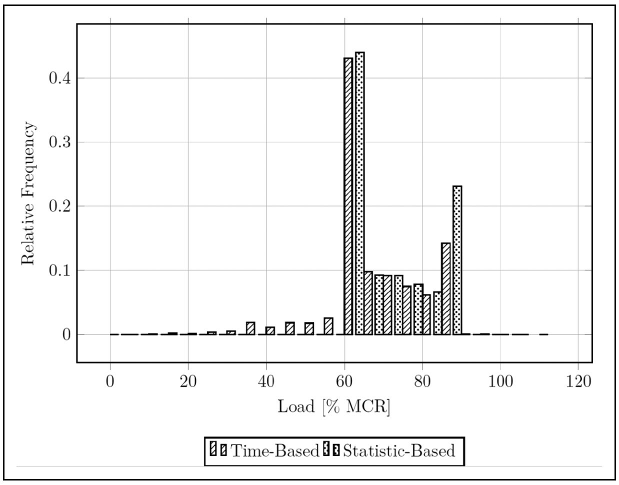

Figure 4. Histogram of the engine load for the time- and statistic-based calculation.

3. When the state of charge does not reach its limits, because of a sufficient capacity, the fuel savings should be coherent in both calculation approaches.
4. Reaching stage of charge limits would lead in reality to turning off or on of engines. A too small battery capacity would lead to frequent starting and stopping of engines. Without temporal connection this cannot be investigated.
5. It cannot be observed, if the power supply is temporarily insufficient due to an empty battery.
6. Efficiency gain due to load leveling and eventually peak shaving is only considered using the suggested more complex statistical approach.
7. As the battery has effectively an infinite capacity from statistical perception, optimal sizing is not possible.

This section has shown that the statistical approach can be used for a rough evaluation of the hybrid system. However, for an exact estimation of the battery life and the case-by-case consideration, time series have to be established. Since the potential of the hybrid system can be estimated by simple means, it can be decided beforehand whether a costly generation of time series is worthwhile or not. Only then it can be determined whether the battery capacity is sufficient for the transport task. Also, to determine the state of charge upon arrival at the port (e.g. for emission free port operation), the time sequence of events must be available.

Influence of neglecting load variations

As seen in Section 2, idealized data with constant power segments in the times series are often used as data basis. Hence, the importance of taking load variations into account is examined. Originally the required power was recorded for every second. For the examination the 1-, 5-, and 15-min average was determined from the measured data of 1 year. Figure 5 displays exemplarily the different time series for going back and forth. With every time series the same hybrid setup was calculated. Section 5.2.1 reviews the results of different smoothing and Section 5.2.2 discusses the differences.

Comparison of the results. To compare the influence of different time step sizes the results of key parameters are examined (see Table 3). Firstly, the possible fuel savings are opposed and subsequent the deviation of the fuel consumption, the charge cycles of the battery and the operational hours from the second-by-second calculation. About 2.10% fuel savings were determined in Section 5.1.1, which is higher than 1.47%, 1.28%. It has to be mentioned, that also the fuel consumption of the conventional reference system changes. Generally, the different interval sizes have only little influence on the overall fuel consumption itself. The obtained charge cycles decrease by −2.23%, −5.63%, and −21.05% with less load variations in the data. Also, the results for the operational hours lead to a reduction (−2.02%, −3.03%, and −3.65%), even though not as significant for the 15-min average. Figure 6 shows extracts of the calculation for illustration. A time frame of going back forth was chosen, hence the constant power section between about 60 and 80 min resembles the call to port. In those figures the required power, the engine power and battery power is plotted. It can be seen, that as long as the engines operate in the preset efficiency range, they provide the required power (e.g. between 5 and 20 min the engine and the required power is overlapping). As soon as the efficiency range would be exceeded, the battery supports accordingly (e.g. see 20–40 min). Positive battery power means power supply and negative power means storing power. Additionally, the state of charge is displayed, which increases and decreases respectively. The maximum state of charge is reached two times throughout the example. At about 45 and 80 min it can be seen, that significant higher load peaks are smoothed.

Discussion of the results. Beforehand, two main outcomes were expected, when neglecting load variations:

- Load leveling or peak shaving is less represented, thus the efficiency gain turns out smaller.
- Charge cycles are underestimated.

The first assumption would have led to higher fuel consumption in the battery supported system and consequently to less fuel savings. In contrast, the results have shown only minor changes of the overall fuel consumption for the conventional and hybrid calculation. Nevertheless, as the results of the conventional setup decrease slightly more, smaller fuel savings are seen for the smoothed data. Hence, the outcome is as expected, but not due to the mentioned reason. The second assumption is explained by the fact, that the stage of charge follows the load variations. Because of fewer fluctuations in the battery power, the stage of charge experiences fewer changes. This is exemplarily illustrated comparing the blue/dotted line in Figure 6(a) (every second) and Figure 6(b) (5-min average) between 80 and 120 min. While the reference calculation experiences an up and down in the state of charge, the 5-min average sees a stepwise increase. This is the result of a reduced battery activity, because the engines can handle the load changes efficiently. This observation is also confirmed in the overall results from 1-year calculation of the charge cycles (see Table 3) and leads to about 0.25, 0.65, or 2.85 years overestimated lifetime (based on lifetime calculation from Emmersberger et al.[28]).

Concluding remarks. The insufficiency of idealized and simplified time series can be summarized:

1. Load fluctuation contribute to the number of charge cycles, which is important for lifetime estimations of the battery
2. Neglecting load variation leads to less fuel savings. It could not be verified, that this is due the underrepresentation of load leveling or peak shaving. Main effect was the lesser fuel consumption in the comparative calculation.
3. In periods of maneuvering more power is needed at low speed, than the speed-power curves can

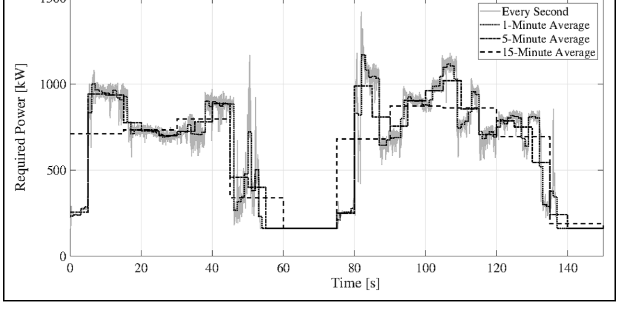

Figure 5. Excerpt of the required power for the original data, 1-, 5-, and 15-min average.

Table 3. Differences of the calculation results from the original measured data compared with the 1-, 5-, and 15-min average.

	Data resolution		
	1-min	5-min	15-min
Fuel savings (%)	1.47	1.41	1.28
	Deviation from the original data		
FOC[a] (Conv.) (%)	−0.47	−0.53	−0.66
FOC[a] (Hybr.) (%)	−0.14	−0.14	−0.14
Charge cycles (%)	−2.23	−5.63	−21.05
Operational hours (%)	−2.02	−3.03	−3.65

[a]Fuel oil consumption.

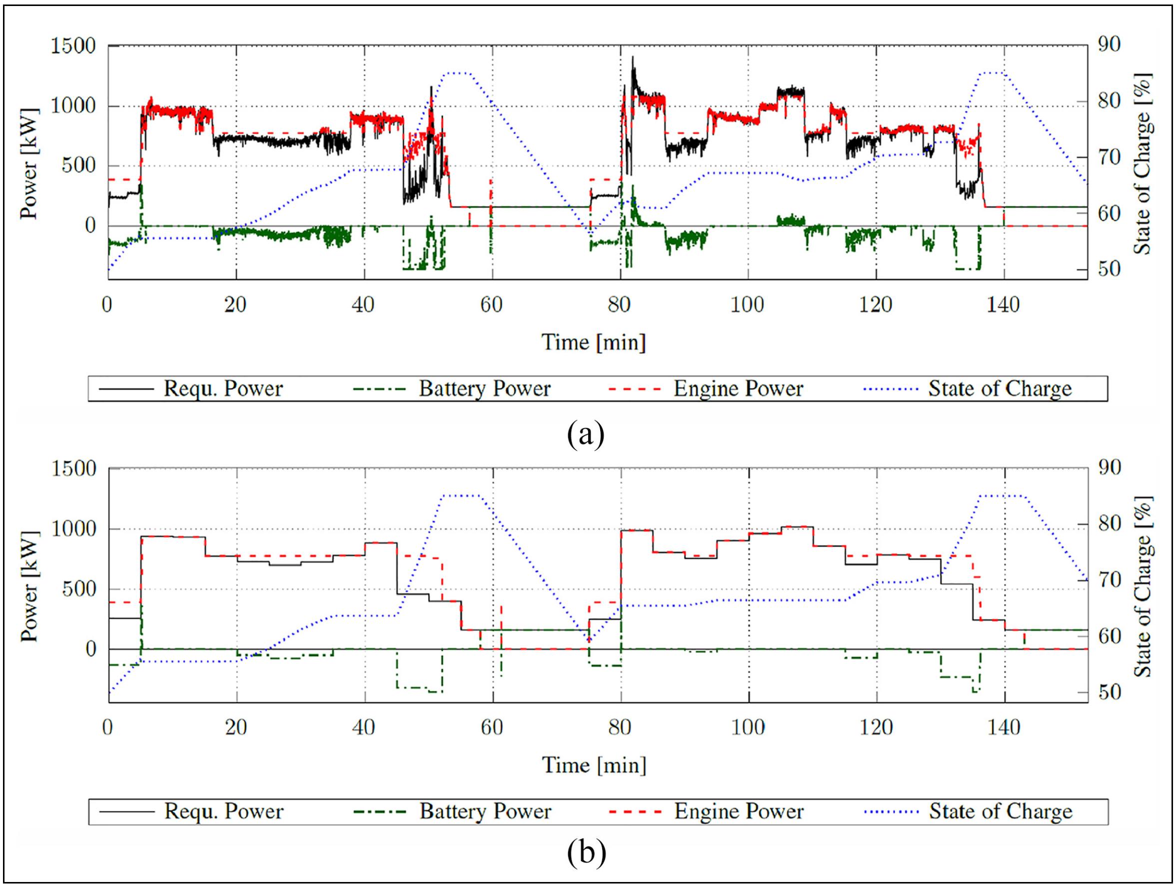

Figure 6. Exemplary excerpt of the calculation with the original data (every second (a)) and the 5-min average (b). It depicts the power distribution of the required power between the engines and battery and the state of charge. One round trip of the ferry is shown.

predict. Thus, derived time series of the required power can be inaccurate.

4. The reliability of supply at maximum load can't be ensured.

Conclusion

This paper examined the influence of the data basis on the evaluation of a hybrid energy system with battery assisted diesel-electric propulsion. A comparison of a statistic-based and time-based approach was under taken. Furthermore, the effect of the time series resolution of the required power as input data was discussed. Therefore, measured data of a double-ended ferry was used with an in-house calculation method for dimensioning hybrid ship drive systems. As the results and insights in this paper were developed from this specific case, the transferability to similar application needs to be checked. Moreover, an enhanced statistical method was introduced, which exceeds common approaches using temporal distribution of operating modes. The investigation has shown, that the extended statistical approach generates valuable results for assessment of the hybrid ship drive system. The fuel savings, operating hours and charge cycles can be predicted. Nevertheless, several considerations, like the wrong efficiency gain prediction, underestimation of the fuel consumption and the optimal sizing of the battery have to be taken into account. Beyond that, it was confirmed, that neglecting load variations lead to an underestimation of the battery charge cycles, which leads to an overestimation of the battery life time. Likewise, the actual efficiency gain turns out smaller. Summarized, a simplified data basis can lead to an inaccurate or misleading assessment of hybrid ship drive system. One of the reasons is the dynamic behavior of the battery due to the dependence of the state of charge on preceding conditions. The general potential of battery supported ships can be estimated with the in-house statistical approach. Still, even small load variations have an influence on the system. The found outcome contrasts with the availability of accurate input data in the early design stage (as e.g. from measurements). Therefore, a straight-forward method to generate time series of the propulsion power is needed, which will improve the dimensioning and the evaluation of hybrid ship drive systems. Especially as changes in the configuration in a later design stage or even during production are very expensive. For this purpose, the force based maneuvering simulations[8,9] can be extended to incorporate the temporal dependencies and encompass the entire life cycle by using Eljardt's[5] approach. As the numerical approach is developed for the early design the simulation should be sufficiently rapid, which future work will show.

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