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Optimized use of Energy Charged from Shore in Plug-in Hybrid Marine Vessels

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Abstract. The paper presents a methodology for the design and tuning of real-time power and energy management systems for plug-in marine vessels. Main contributions are: (1) Method to design and tune the energy management strategy that will optimally share the load between on-board, fixed speed, diesel generator units and on-board energy storage, in such way that fuel consumption is minimized for a given expected load probability distribution (2) Method adaption for cases where the crew, for operational or safety reasons, decides to run with non-optimal number of diesel engines. (3) Outline of possible inclusion of adaptive tuning to cope with uncertain or unknown load probability distribution. The presented methodology applies to plug-in vessels where the battery storage cannot cover all energy needed for the planned trip, such that one need to combine the use of stored electrical energy from shore with the direct use of energy produced by on-board diesel generators. The proposed method uses the expected time of operation at each load level as key input for the optimization. Although getting such data upfront can be difficult, it is expected to be easier to get a good estimate of the load probability distribution rather than the exact load profile as function of time that is used by the existing methods.

1. Introduction

All electric ships have over the last decades become more and more common, and recently it is also seen that battery energy storages are installed as a supplement or replacement for the traditional onboard diesel generators [1]. The benefits of such hybrid power systems with energy storages are summarized in [2]. A review of the developments within design and control of hybrid power and propulsion systems for ships with hybrid power plants can be found in [3].

This paper addresses the optimal operation of hybrid marine vessels with multiple diesel engine generators and energy storage where the use of energy charged from shore is the main motivation of having the energy storage installed. The use of shore energy helps reducing fuel consumption and emissions and is also one way of lowering operating costs in countries where electric energy from the main grid is cheaper than electricity produced by onboard diesel engine generators. Examples of such vessels can be ferries that cannot be fully electrified due to the combination of crossing distance, charging facilities, crossing frequencies and investment cost. Service vessels for the offshore wind and oil and gas installations as well as fishing vessels are other examples.

For these vessels, the use of the energy stored from last shore charging must be optimized to achieve minimum fuel consumption for the completion of the planned mission. At the same time, it is also desired to control the use of energy in such way that the state of charge of the storage at time of arrival is at a level that allows for full utilization of the charging facility during the stay.

As pointed out in [2], there are several other motivations for introduction of energy storage in marine power systems than the utilization energy charged from shore for fuel consumption reduction. Storage can be included to allow for strategic loading of engines where storage is both charged and discharged during the trip to keep the engines operating closer to their optimal loading point and thereby giving higher efficiency. Storage can also be used as spinning reserve to reduce the need of having additional engines running as a reserve in case of sudden increase in load or sudden loss of power producing units. Storage can also be used as power source in harbor to reduce the need for running engines at very low load as well as to avoid installation of a dedicated harbor generator. Finally, storage can be used to improve on-board electric power quality by providing short-term dynamic support and load-peak shaving.

There are several examples from literature addressing the fuel-optimal operation of hybrid power plants [4]-[10], using different methods of optimization. However, common to all the methods, optimization is performed towards measured or estimated time domain load series. Moreover, there is no attempt to optimize the strategy towards a specific load variation. In contrast, the method presented in this paper takes the load variation into account and uses the load probability rather than time series as basis for the optimization. The benefit of such approach is that it will not be sensitive towards the sequence of the load variation. The power management strategy presented in this paper is to use stored energy whenever the corresponding specific fuel saving ψ is above a given threshold. What is optimized is the specific fuel saving threshold ψ_{opt} that maximizes the fuel saving for a given load variation and a given amount of stored energy. This is different from a general optimization approach, where the strategy is the result of the optimization itself.

A related approach for design of minimum fuel consumption energy management strategy for hybrid marine vessels with multiple diesel engine generators and energy storage was presented in [11]. The method presented in [11] addressed strategic loading of the engines and was only applicable to vessels that do not charge from shore. This paper extends such method by including the optimal spending of energy charged from shore. Further, the paper shows how the method can be adapted for cases where one, for operational or safety reasons, decides to run with non-optimal number of diesel engines. Finally, it presents tuning alternatives in case of irregular or unknown load distributions.

It is emphasized that the methods discussed in this paper can be relevant also in case the main motivation for storage installation is for instance for spinning reserve in dynamic positioning mode (DP). If the vessels have access to charging facilities and if it is acceptable and safe to spend some of the energy, then it is also relevant to optimize the use of the stored energy for such vessels.

The advantages of the proposed method is that it is deterministic, and relatively easy to implement in a real system. The computational burden during operation will be low.

The optimization in this paper is limited to finding the power management strategy that maximizes the fuel saving for a predefined system. It is emphasized that maximum fuel saving does not guarantee minimum cost. The presented method can however be incorporated in cost optimization methods.

2. Case study

To illustrate the principles, the proposed methodology is applied to the hybrid system shown in Figure 1, consisting of an energy storage and four identical diesel engines, each rated for 0.6 MW and optimized for 80% of maximum continuous operation (MCO). The specific fuel consumptions for one to four diesel engines running in parallel are shown in Figure 2. Shown in the same figure is also the minimum specific fuel consumption (SFC) achievable by selecting the number of running engines n according to the load level, assuming no required spinning reserve:

$$SFC_{DG,opt,n>0}\left(P_{L}\right) = \min_{n=1,\ldots,4}\left(SFC_{DG}\left(n,P_{L}\right)\right) \tag{1}$$

The two battery storage systems in Fig. 1, storage converters included, are treated as an aggregate system whose operating losses while discharging are expressed as:

$$P_{l,D} = f_{2}(P_{B,D}) = p_{l,0} \cdot P_{B,rated} + p_{l,D} \cdot P_{B,D} \tag{2}$$

where $P_{B,D} \geq 0$ are the discharging power and $P_{B,rated}$ is the rated power of the battery storage. The system parameters are reported in Table 1. In the following, it is assumed that operation with storage only (no running engine) is acceptable. The presented method can however be easily extended to include a constraint on the minimum number of running engines, as will be shown in section 5.
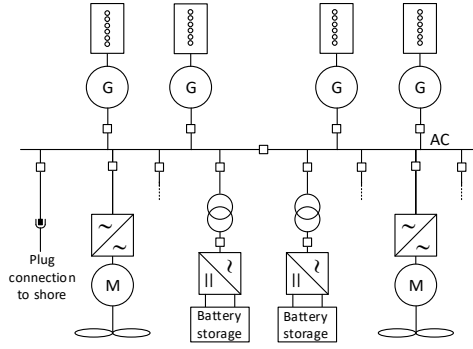

Figure 1. The plug-in hybrid system. Parameters for the system are reported in Table 1.
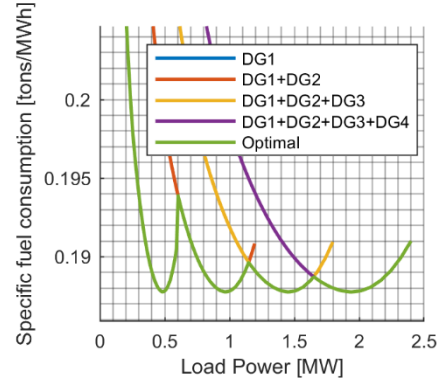

Figure 2. Specific fuel consumption (tons/MWh) for 1-4 engines $SFC_{DG}(n,P_L)$. Green line shows best operation without storage and without spinning reserve $SFC_{DG,opt,n>0}(P_L)$.

3. Optimizing the use of energy charged from shore

The fuel saving achievable by using the energy available in the storage after shore charging depends on the operating strategy, since the fuel consumption of the engines and the storage system discharge losses are non-linear with respect to loading and discharge power level. Under the assumption of no direct flow of energy from the on-board generators to the storage (only charging from shore is allowed), an optimal strategy is devised going through the following steps:

- Find fuel saving per unit of time, Δfc_{SP}, at different specific load levels P_L for all possible power splits between storage and DG units.
- Find the specific fuel saving per used unit of energy, ψ, at different specific load levels P_L for all possible power splits between storage and DG units.
- Find the relationship between the expected time the vessel will operate at each P_L, and the corresponding maximum stored energy, W_{tot}, that in a given time period T_0 can be utilized if one requires the fuel saving to be above a minimum specific fuel saving threshold ψ_{th}
- Finally, find the optimal threshold $\psi_{th,opt}$ that defines the power management strategy that maximizes the fuel saving for the given W_{tot}.

3.1. Mapping the fuel saving potential

Let us assume that at the start of a trip of time duration T_0 a given amount of energy is available in the on-board storage. Determination of the optimum strategy for using the available energy in the storage starts from considering steady-state operation at a specific load level P_L. In general, the load power can be supplied partly by the DG units, $P_{DG,SP}$, and partly by the storage unit, $P_{B,DSP}$, with:

$$P_{DG,SP} = P_L - P_{B,DSP} \tag{3}$$

$$P_{B,DSP} \leq P_L \tag{4}$$

$$0 \leq P_{B,DSP} \leq P_{B,\max,D} \tag{5}$$

What is needed is a strategy for choosing $P_{B,DSP}$ at different load levels P_L to maximize fuel saving. A common strategy consists in selecting the value of $P_{B,DSP}$ that minimizes the fuel consumption per hour operation. This corresponds to always supplying as much power as possible from the storage:

$$P_{B,DSP,ref}(P_L) = \min \begin{cases} P_L \\ P_{B,\max,D} \end{cases} \tag{6}$$

This natural strategy will generally not be optimal unless the storage power and energy rating is large enough to supply the load for the whole trip. If stored energy is limited, then the total saving will be maximized if energy is used at the load levels that gives most fuel saving for each unit of stored energy.

The minimum fuel consumption per hour for a given combination of load and storage power is expressed as:

$$fc_{SP}(P_{DG,SP}) = P_{DG,SP} \cdot SFC_{DG,opt}\left(P_{DG,SP}\right) \tag{7}$$

The optimum specific fuel consumption defined in (1) can be extended for use in (7) as follows, if battery storage is included and operation with no running engines is also allowed:

$$SFC_{DG,opt}\left(P_{DG,SP}\right) = \min \begin{cases} \min_{n=1,\ldots,4}\left(SFC_{DG}\left(n,P_{DG,SP}\right)\right) & \{P_L > P_{B,\max,D}\} \\ 0 & \{P_L \leq P_{B,\max,D}\} \end{cases} \tag{8}$$

Optimal number of running engines during storage discharge, $n_{D,opt}(P_L)$, that minimizes specific fuel consumption at a given load is implicitly given by (8).

Resulting fuel saving per hour is evaluated by taking fuel usage at load level $\bar{P}_L$ operating with optimal number running of DG units and no storage power and subtract the fuel usage in case storage power is used:

$$\Delta fc_{SP}(P_L, P_{DG,SP}) = P_L \cdot SFC_{DG,opt,n>0}\left(P_L\right) - fc_{SP}(P_{DG,SP}) \tag{9}$$

To determine at which load levels it is most favorable to spend the energy charged at shore, the fuel saving per unit of used storage energy must be evaluated. At first, an expression for the time needed to spend a certain amount of energy ($W_{B,out}$) from storage at a given load level is written, taking the discharge losses ($P_{l,D}$) into account:

$$T_{D,SP}(P_{B,DSP}) = \frac{W_{B,out}}{P_{B,DSP} + P_{l,D}} \tag{10}$$

The total fuel saving ΔF resulting from the use of $W_{B,out}$ energy from storage at load level P_L is then:

$$\Delta F(P_L, P_{DG,SP}, P_{B,DSP}, W_{B,out}) = \Delta fc_{SP}(P_L, P_{DG,SP}) \cdot T_{D,SP}(P_{B,DSP}) \tag{11}$$

Fuel saving per unit of energy from shore, or the specific fuel saving ψ, can now be found from:

$$\psi(P_L, P_{DG,SP}, P_{B,DSP}) = \frac{\Delta F(P_L, P_{DG,SP}, P_{B,DSP}, W_{B,out})}{W_{B,out}} = \frac{\Delta fc_{SP}(P_L, P_{DG,SP})}{P_{B,DSP} + P_{l,D}} \tag{12}$$

Specific fuel saving (ψ) are then known for any combination of P_L and $P_{B,DSP}$ satisfying (3), (4) and (5). The load power P_L that maximizes (12) corresponds to the best operation point to spend one unit of shore energy. Specific fuel saving for the example case under the assumption of maximum storage power limited to 0.6MW (ref. Table 1) is illustrated in Figure 3, while Figure 4 shows the maximum and minimum values of ψ at different vessel loads. It is to be noted, that there will be some fuel saving no matter how the stored energy are spend as long as one does not run more engines than what is optimal in order to supply the share of the load that are not supplied from the battery. It can be observed in the

figures that even the worst-case power split gives significant fuel saving. As soon as shore energy is used, less energy needs to be supplied from the engines and consequently there will be some fuel saving.
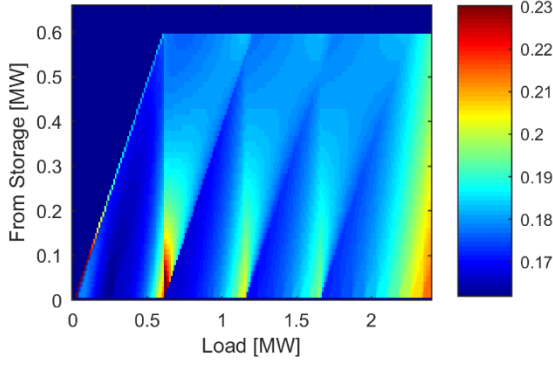

Figure 3. Specific fuel saving, $\psi(P_L, P_{DG,SP}, P_{B,DSP})$, for the example case in section 2. Figure shows the tons of fuel saved per used MWh energy from storage for different usage of stored energy at different vessel loads.
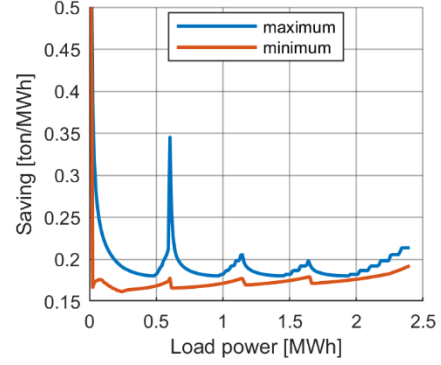
Figure 4. Maximum and minimum specific fuel saving (ψ) at different vessel loads.

Having mapped the fuel saving potential, it is possible to find the maximum storage power $P_{B,DSP,max}$ at each load level that as a minimum gives a specific fuel saving above a threshold ψ_{th}:

$$P_{B,DSP,max}(P_L, \psi_{th}) = \max \left(P_{B,DSP}, \begin{cases} \psi(P_L, P_{B,DSP}) > \psi_{th} \\ P_{B,DSP} \le P_L \\ 0 \le P_{B,DSP} \le P_{B,max,D} \end{cases} \right) \tag{13}$$

Figure 5 shows examples of maximum storage power at each load level for three different specific fuel saving thresholds. Also shown is the corresponding power to be supplied from the DG units. Similar plots can be made for any value of ψ_{th}. As will be shown in the following, these defines potential optimal power split between DG units and storage.

Let us assume that the load distribution is known for the time interval T_0 of the trip. The (expected) relative time spend at a given load level $\alpha(P_L)$ is such that

$$\int_0^{P_{L,max}} \alpha(P_L) \cdot dP_L = 1 \tag{14}$$

where $P_{L,max}$ is the maximum load of the vessel. Figure 6 shows an example of a load distribution. It is now possible to find the maximum storage energy $W_{tot}(\psi_{th})$ that can be used within a time interval T_0 with load distribution $\alpha(P_L)$ as function of specific fuel saving threshold ψ_{th}:

$$W_{tot}(\psi_{th}) = T_0 \cdot \int_0^{P_{L,max}} (P_{B,DSP,max}(P_L, \psi_{th}) + P_{l,D}(P_{B,DSP,max})) \cdot \alpha(P_L) \cdot dP_L \tag{15}$$

Figure 8 shows the total used energy from storage (in percent of total demand) for different thresholds ψ_{th}, for the example vessel operated with the load distribution profile shown in Figure 6.
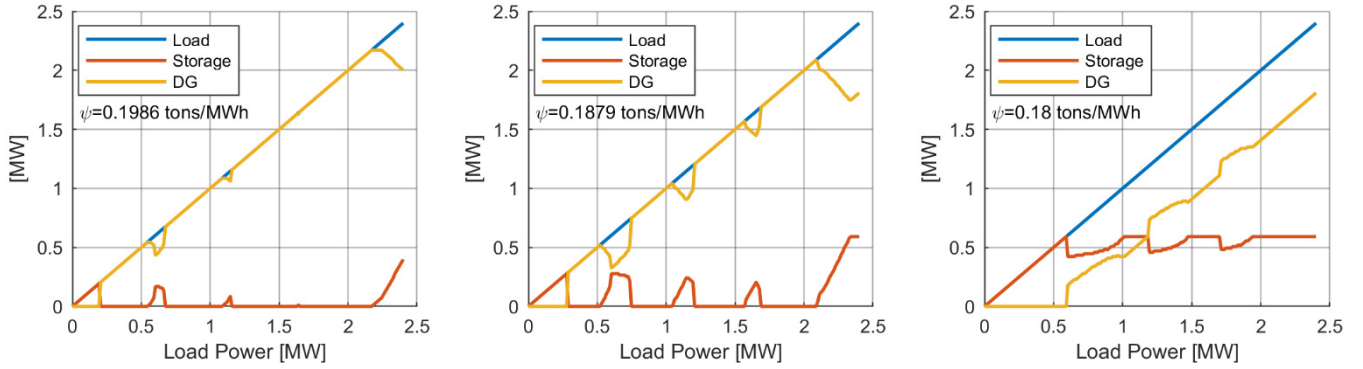
Figure 5. Maximum storage power usage at different load levels for three different specific fuel saving thresholds, from left to right: $\psi_{th} = 0.199$, $\psi_{th} = 0.188$ and $\psi_{th} = 0.180$. Red lines show the optimal storage power $P_{B,DSP,\max}(P_L, \psi_{th})$ from (13) and yellow lines show the corresponding DG power at each load level. Blue shows the load power.
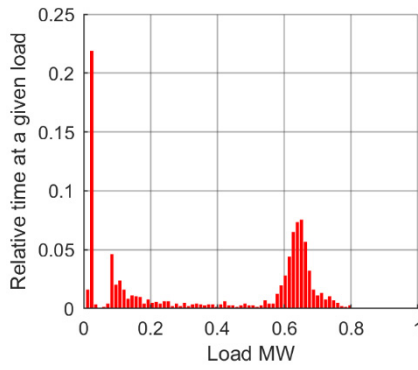

Figure 6. Expected relative time the example Vessel will operate at different load levels ($\alpha(P_L)$)
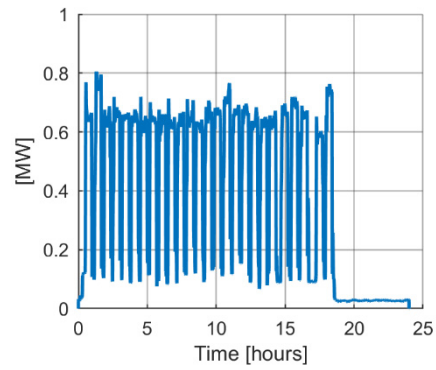

Figure 7. Example load variation as function of time. The load distribution of this time series corresponds to Figure 6 and is used in the time domain simulations in section 4.

3.2. Optimal specific fuel saving threshold

Knowing the total energy that can be charged from shore $W_{B,T0}$ and the vessel load distribution $\alpha(P_L)$ the specific fuel saving threshold $\psi_{th,opt}(W_{B,T0})$ that minimizes fuel consumption can be evaluated. This optimum will implicitly ensure that all available energy from shore is utilized whenever this is possible. In some cases, it will not be possible to ensure that all stored energy is used during the trip simply because the stored energy is larger than the energy needed for the trip. In some cases, it can also be impossible to spend all stored energy even if the trip requires more energy than what is stored. This may happen if the storage maximum power rating is less than the maximum load power. Some of the energy will then have to be supplied from the engines, no matter how the storage is utilized.

The optimal threshold $\psi_{th,opt}$ for maximum fuel saving can be found using (15) and setting $\psi_{th} = \psi_{th,opt}$ and $W_{tot}(\psi_{th}) = W_{B,T0}$:

$$W_{B,T0} - T_0 \cdot \int_0^{P_{L,\max}} (P_{B,DSP,\max}(P_L, \psi_{th}) + P_{l,D}(P_{B,DSP,\max})) \cdot \alpha(P_L) \cdot dP_L = 0 \qquad (16)$$

Equation (16) can be solved numerically, and the results for the example vessel are shown in Figure 8. Note that optimal threshold $\psi_{th,opt}$ will be zero for cases where $W_{B,T0}$ is too large to find a solution of (16) since the strategy then will have to be to use as much as possible all the time with no minimum required specific fuel saving threshold.
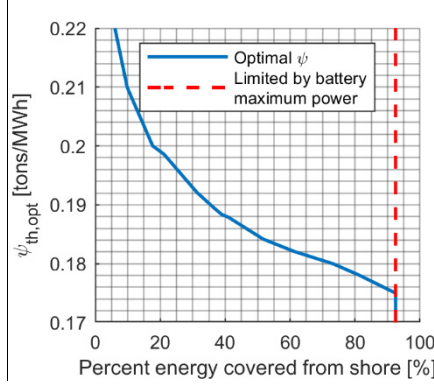

Figure 8. Figure shows $\psi_{th,opt}(W_{B,T0})$ (and also $W_{tot}(\psi_{th})$). The x-axis is in in percentage of sum load energy demand.   (valid for the load distribution in Figure 6)
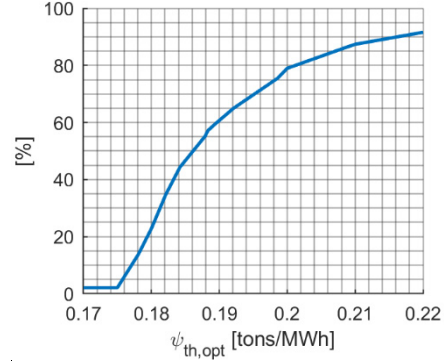
Figure 9. Fuel usage for different values of $\psi_{th,opt}$ in percent of fuel usage with no storage for different specific fuel saving thresholds.

Once the optimal threshold for the specific fuel saving is determined, the optimal operation strategy is implemented by using the storage power at each load level P_L according to:

$$P_{B,DSP,opt}(P_L,W_{B,T0}) = P_{B,DSP,\max}(P_L,\psi_{th,opt}(W_{B,T0})) \tag{17}$$

Power from DG units at each load level for optimal use of the stored energy, $P_{DG,SP,opt}$ is then simply following from the power balance in (3):

$$P_{DG,SP,opt}(P_L,W_{B,T0}) = P_L - P_{B,DSP,opt} \tag{18}$$

The corresponding optimal number of running DG units (n_D) can then be found from (8). The optimal number of running engines will be the one that minimizes SFC_{DG} in (8) when $P_{DG,SP} = P_{DG,SP,opt}(P_L,W_{B,T0})$.

Fuel saving for the proposed optimal shore energy usage strategy is then calculated as:

$$\Delta FC(W_{B,T0}) = T_0 \cdot \int_0^{P_L} \alpha(P_L) \cdot \Delta fc_{SP}(P_L,P_{DG,SP,opt}) \cdot dP_L \tag{19}$$

Fuel usage for the example vessel in percent of the no-storage case is in Figure 9 shown for different values of $\psi_{th,opt}$.

3.3. The optimized, rule-based power management strategy

The results of the previous section can be used to devise an optimized, rule-based power management algorithm. Tabulated schemes for power split between storage and engines are first determined for a range of different ψ_{th} (similar to those plotted in Figure 5).

Ahead of each trip of duration T_0, an estimation of the total energy from shore will be available. The system can then use (16) to find the corresponding optimal $\psi_{th,opt}$ (or use Figure 8 to read out the value). The power split will then be controlled such that it follows the scheme established for the $\psi_{th} = \psi_{th,opt}$ (exemplified in Figure 5 for three different $\psi_{th,opt}$)

3.4. Battery degradation

Battery degradation has not been addressed in this work. For a plug-in hybrid charged only from shore, the major factors that influence the storage degradation will be the amount of energy charged from shore ($W_{B,T0}$) and the maximum allowed storage power flow ($P_{B,\max,D}$). None of these are determined by the optimization presented here. It is therefore not considered relevant to consider battery degradation effects in the optimization of the operating strategy. The battery degradation effects need however to be taken into consideration when the battery system rating is selected. Battery storage degradation also needs to be included when deciding what will be the optimal amount of energy to take from shore ($W_{B,T0}$). Storage sizing and optimal amount of shore energy to use is however beyond the scope of this work.

4. Time domain simulation

Time domain simulations have been performed to illustrate the effect of different energy management strategies. Figure 7 shows an example of a time domain load series that corresponds to the load distribution in Figure 6, already used to exemplify the method. The time domain load series is based on load profiles typical for hybrid ferries. A duration T_0 of 24 hours has been assumed for the complete load cycle.

The system parameters used in the simulations are shown in Table 1. Two cases have been analyzed, respectively with 20% and 40% of the load energy covered by shore energy. Both cases have been simulated with a range of different values of ψ_{th}, including the optimal $\psi_{th,opt}$ calculated for each case. In the simulations the energy management strategy for each selected ψ_{th} was derived from (13) (see Figure 5 for examples). Fuel saving compared to operation without battery was recorded for each simulation and the results are shown in Figure 10. It can be seen that the choice of ψ_{th} has noticeable impact on the resulting fuel saving and that there is an optimum. Moreover, the optimum $\psi_{th,opt}$ predicted from (16) or Figure 8, corresponds very well with the ψ_{th} that gave maximum fuel saving in the simulations.
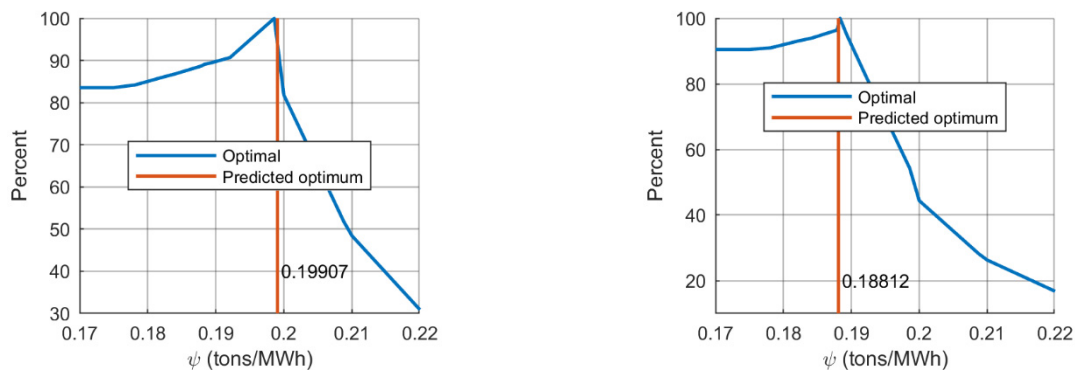

Figure 10. Fuel saving relative to the maximum fuel saving for different threshold values of ψ for the two cases 20% (left) and 40% (right) of energy taken from shore. Optimization using (16) or Figure 8 predicted maximum fuel saving for the thresholds $\psi = 0.199$ and $\psi = 0.188$ (the vertical lines)

Figure 11 presents time domain results for two different ψ_{th} for the case with 20% load energy covered by storage. The left plot shows the consequence of setting a too low ψ_{th}. Excessive use of storage takes place in the beginning of the time period T_0. The consequence is that storage is empty after about 9 hours, with no stored energy left to maximize saving during the remaining part of the trip. The right plot shows the opposite, with a too large ψ_{th} giving a very conservative use of storage energy such

that about 50% of the storage energy remains unused at the end of the trip. The optimal use of storage power is shown in Figure 12 for $\psi_{th,opt} = 0.199$. This corresponds to the simulation that gave the maximum fuel saving in Figure 10.

Figure 13 shows the optimal use for 40% energy from storage. It can be seen that the use of storage power is more intensive compared to the case of 20% storage power (Figure 10.)

For simplicity, the 24 hours were in this example treated as one trip, although in practice, a ferry will typically recharge many times during the day. The results presented in the example are therefore strictly only valid for the case that the battery is fully charge only at the beginning of the simulated interval and that the recharging during the day is not able to bring the battery back to fully charged.
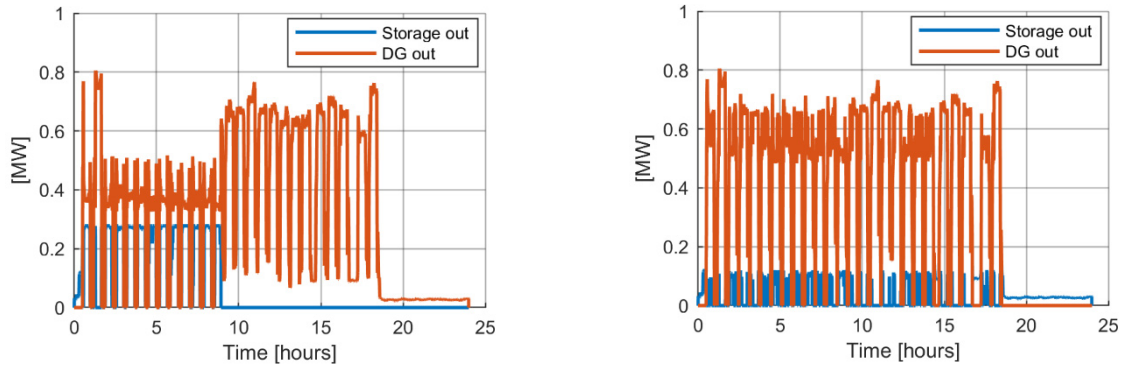

Figure 11. Non-optimal split between storage power and DG power for 20% of load power supplied from shore. The use of storage power is too intensive in the left figure, corresponding to $\psi_{th} = 0.188$ in Figure 10. The right figure shows a simulation with 20% energy available and $\psi_{th} = 0.209$. This shows an example of too conservative use of energy, resulting in about 50% of unused available energy from shore at the end of the period T_0 (24 hours).
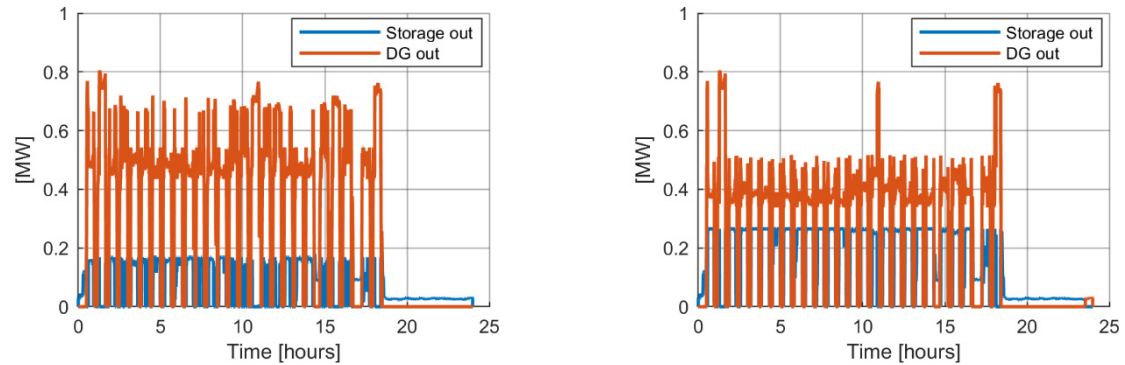

Figure 12. Optimal split between storage power and DG power for 20% of load power supplied from shore $\psi_{th} = \psi_{th,opt} = 0.199$

Figure 13. Optimal split between storage power and DG power for 40% of load power supplied from shore $\psi_{th} = \psi_{th,opt} = 0.188$

5. Optimization for non-optimum number of running DG units

In many practical applications, it will not always be possible to run exactly the optimum number of DG units, either because of safety, operational procedures or because one chooses to restrict the number of DG start and stops. It is therefore relevant to extend the energy management strategy to such non-ideal situations. The proposed method allows for simple adaptation, consisting in the use of $SFC_{DG,opt}\left(P_L, n_{min}\right)$ instead of $SFC_{DG,opt}\left(P_L\right)$, where:

$$SFC_{DG,opt}\left(P_L, n_{min}\right) = \min_{n=n_{min},\ldots,4}\left(SFC_{DG}\left(n, P_L\right)\right) \tag{20}$$

Using $SFC_{DG,opt}\left(P_L, n_{min}\right)$, (7) and (9), we can get the specific fuel saving (ψ_n) for minimum $n = n_{min}$ running DG units:

$$\psi_n(P_L, P_{DG,SP}, P_{B,DSP}, n_{min}) =$$
$$\frac{P_L \cdot SFC_{DG,opt}\left(n_{min}, P_{DG}\right) - P_{DG,SP} \cdot SFC_{DG,opt}\left(n_{min}, P_{DG,SP}\right)}{P_{B,DSP} + P_{l,D}} \tag{21}$$

Expression (21) can now be used in the same way as (12) to create a strategy for when to use shore energy in case a certain minimum number of running engines is prescribed.

6. Alternative approaches for unknown load profiles

6.1. Manual tuning
Instead of finding optimal ψ_{th} to use in (13) for a given load profile and given energy from shore, one may also use the ψ_{th} as a setting controlled by the crew. This can be more feasible if no load distribution profile is likely to be representative for the individual trips or if energy from shore is charged at irregular intervals. Based on experience from previous trips, the crew can learn how to choose the optimal ψ_{th}, that is, to set it large enough to prevent using all stored energy long before the trip ends, without setting it too large to avoid reaching the end of the trip with unused energy in the storage.

6.2. Self-learning or artificial intelligence
An alternative to manual tuning is to use some kind of artificial intelligence or self-learning system to tune ψ_{th} ahead of a trip as well as during the trip. Such systems can utilize logged data from previous trips as well as any other available data that can be used to estimate load profile for the remaining trip. Relevant information can be gathered automatically (e.g. GPS position and energy storage state of charge) or entered by the crew (e.g. destination, type of mission, estimated trip duration). Based on the inputs, the artificial intelligence or self-learning system can select the best ψ_{th} to use for the rest of the trip in order to maximize fuel saving. The chosen ψ_{th} and (13) will then define the optimal use of the storage (the power-split). In such scheme, ψ_{th} can be set to be updated on regular basis during the trip to ensure that, at any time, the storage is utilized in the best way based on the available knowledge about remaining stored energy and expected load distribution for the rest of the trip. The principle is illustrated in Figure 14.

7. Discussion
The additional fuel consumption caused by repeatedly starting and stopping DG units was not included in the optimization. It is likely that certain load variations will cause a large number of start and stops if one follows strictly the suggested optimal split between storage and engines. Common adaptions, such as start and stop delay timers may be needed to prevent too frequent starting and stopping. This will reduce the fuel saving compared to the ideal case. However, the method is still applicable since one may then use the approach described in section 5. to determine the optimal split with non-optimal number of engines.

It is emphasised that the added value of optimizing the use of energy from shore is application dependent. In some cases, there will be a significant added potential in the optimization while in others the optimization might give only insignificant fuel saving compared to less structured use of the stored energy. Differences in added value of optimization will be seen due to variation in shape of the specific fuel consumption curve, the number and rating of DG engines relative to the power rating of the storage as well as the amount of energy that can be taken from shore. The characteristics of the storage system discharge losses will have an impact as well. Finally, the load distribution will have a major impact on

the fuel saving potential of an optimized use. The results of the case-study presented in this paper can therefore not be used to draw general conclusions regarding the value of doing optimization for a given vessel.

The optimal use of energy from shore depends on the load distribution $\alpha(P_L)$. Since the exact load distribution for a given period is almost never known in advance, a perfect optimization cannot be expected in practice. By inspection of Figure 10, it can be seen that the negative consequences of setting the threshold ψ_{th} too large are more severe than those resulting from a too low setting. This is because the consequence of a too large value is that some of the energy from shore is not used at all, which will drastically reduce the total fuel saving. It can therefore be wise to set ψ_{th} somewhat less than the predicted optimum if the load distribution $\alpha(P_L)$ is very uncertain.

The optimization will be most valuable for cases where the amount of energy from shore is a small part of the total energy needed for the trip. This is natural, since in the extreme case of all energy covered from shore there is obviously nothing to optimize since the load demand dictates the use of storage power.

8. Conclusions

This paper has presented a method to design an energy management strategy that will optimally share the load between on-board, fixed speed, diesel generator (DG) units and on-board energy storage, in such way that fuel consumption is minimized for a given expected load distribution. It has been shown how an optimized loading strategy can be derived based on available stored energy and the expected time of operation at each load level. Time domain simulations confirmed that optimization based on the load distribution correctly predicts the optimum.

The paper has also shown how to adapt the method for cases where the crew, for operational or safety reasons, decides to run with non-optimal number of diesel engines. Finally, it has been suggested how one can build a system that is able to adaptively tune itself to cope with inaccurate or unknown load distributions.

References
[1]　E. Skjong, R. Volden, E. Rødskar, M. Molinas, T. A. Johansen and J. Cunningham, "Past, Present, and Future Challenges of the Marine Vessel's Electrical Power System," in IEEE Transactions on Transportation Electrification, vol. 2, no. 4, pp. 522-537, Dec. 2016. doi: 10.1109/TTE.2016.2552720
[2]　Asgeir J. Sorensen, Roger Skjetne, Torstein Bø, Michel R. Miyazaki, Tor Arne Johansen, Ingrid B. Utne and Eilif Pedersen "Toward Safer, Smarter, and Greener Ships: Using Hybrid Marine Power Plants," in *IEEE Electrification Magazine*, vol. 5, no. 3, pp. 68-73, Sept. 2017. doi: 10.1109/MELE.2017.2718861
[3]　R.D. Geertsma, R.R. Negenborn, K. Visser, J.J. Hopman, "Design and control of hybrid power and propulsion systems for smart ships: A review of developments", Applied Energy, Volume 194, 2017, Pages 30-54, ISSN 0306-2619, https://doi.org/10.1016/j.apenergy.2017.02.060.
[4]　E. A. Sciberras, B. Zahawi, D. J. Atkinson, A. Breijs and J. H. van Vugt "Managing Shipboard Energy: A Stochastic Approach" in IEEE Transactions on Transportation Electrification, vol. 2, no. 4, pp. 538-546, Dec. 2016. doi: 10.1109/TTE.2016.2587682
[5]　M.D.A. Al-Falahi, K.S. Nimma, S.D.G. Jayasinghe, H. Enshaei, J.M. Guerrero, "Power management optimization of hybrid power systems in electric ferries", Energy Convers. Manage. 172 (2018) 50–66.

[6]   A. Anvari-Moghaddam, T. Dragicevic, Lexuan Meng, Bo Sun and J. M. Guerrero, "Optimal planning and operation management of a ship electrical power system with energy storage system," IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society, Florence, 2016, pp. 2095-2099. doi: 10.1109/IECON.2016.7793272

[7]   Thanh Long Vu1, Jaspreet Singh Dhupia1, Aaron Alexander Ayu1, Louis Kennedy2, Alf Kare Adnanes, "Optimal Power Management for Electric Tugboats with Unknown Load Demand, 014 American Control Conference (ACC),June 4-6, 2014. Portland, Oregon, USA

[8]   Bijan Zahedi, Lars E. Norum, Kristine B. Ludvigsen, "Optimized efficiency of all-electric ships by dc hybrid power systems", Journal of Power Sources, Volume 255, 2014, Pages 341-354, ISSN 0378-7753

[9]   M. R. Miyazaki, A. J. Sørensen and B. J. Vartdal, "Reduction of Fuel Consumption on Hybrid Marine Power Plants by Strategic Loading With Energy Storage Devices," in IEEE Power and Energy Technology Systems Journal, vol. 3, no. 4, pp. 207-217, Dec. 2016.

[10] T. L. Vu, A. A. Ayu, J. S. Dhupia, L. Kennedy and A. K. Ådnanes, "Power Management for Electric Tugboats Through Operating Load Estimation," in IEEE Transactions on Control Systems Technology, vol. 23, no. 6, pp. 2375-2382, Nov. 2015. doi: 10.1109/TCST.2015.2399440

[11] O. Mo and G. Guidi, "Design of Minimum Fuel Consumption Energy Management Strategy for Hybrid Marine Vessels with Multiple Diesel Engine Generators and Energy Storage," 2018 IEEE Transportation Electrification Conference and Expo (ITEC), Long Beach, CA, 2018, pp. 537-544. doi: 10.1109/ITEC.2018.8450263
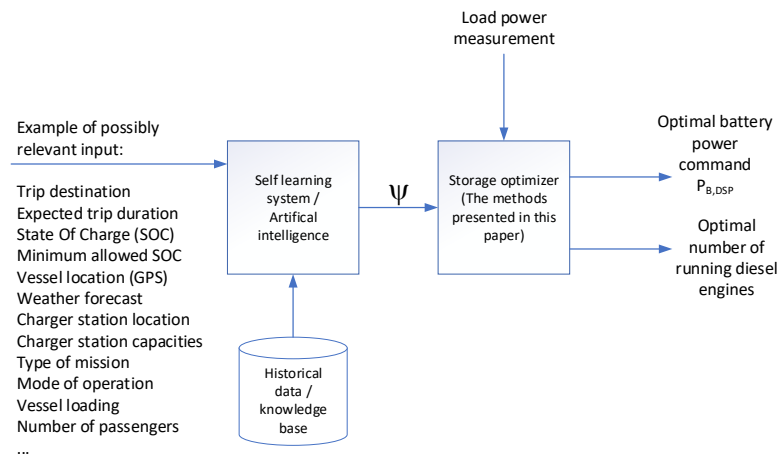
Figure 14. Illustration of possible use of artificial intelligence to retune ψ_{min} during each trip

Table 1.   System data for case study

DG maximum continuous power	$P_{DG,max}$	0.6 MW
DG fuel consumption (generator losses included)		Figure 2
Storage rated / maximum power	$P_{B,rated}$ /$P_{B,max,D}$	0.6 MW
Storage and converter discharge loss coefficient $p_{l,D}$		0.04
Storage and converter constant loss coefficient	$p_{l,0}$	0.0
Propulsion and hotel loads		Figure 6 Figure 7