Cost Assessment of Battery Hybrid Energy Storage System for Full-Electric Marine Applications

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***Abstract*— This paper deals with the optimal sizing and cost assessment of onboard battery hybrid energy storage system (HESS) for full-electric marine applications. In this regard, a harbor tug is selected as the use case and the cost of different full-active HESS topologies is compared against a baseline topology with a single type battery. The NMC and LTO battery chemistries are selected as the high-energy (HE) and high-power (HP) battery technologies in this work. The baseline and HESS battery topologies are sized for a design life of 10 years considering the battery aging. The results show that by a parallel full-active HESS topology, the battery pack cost can be reduced around 28% and 14% compared to a monotype battery topology with LTO and NMC cells, respectively. The results of this study imply that hybridization could be a promising solution to reduce the cost of large batteries within the maritime sector.**

Keywords—battery sizing, hybrid energy storage system (HESS), marine applications, cost assessment, electric harbor tug

I. Introduction

Climate change and global warming due to the usage of fossil fuels are among the serious challenges that the world is facing today. The transportation sector accounts as a major contributor to fossil fuel consumption. Currently, around 90% of the global cargo transportation is related to the maritime sector [1, 2]. Although the shipping industry used to be responsible for 2.2% of the total global greenhouse gas emission in 2012 [3], this contribution is expected to reach up to 18% by 2050 [4]. Hence, strict international regulations have been developed by the International Maritime Organizations (IMO) to reduce the GHG emission levels and push the sea transportation industry toward innovative solutions to tackle this issue [3, 4].

In recent years, marine electrification as a promising solution to move towards zero-emission marine transportation has expanded significantly. The conventional diesel-electric systems, hybrid systems with onboard energy storage, and fully battery-electric are the main electrified systems for marine applications [5]. Nowadays, there is more and more interest in full battery-electric solutions for the maritime sector thanks to the recent developments in the Lithium-ion (Li-ion) battery industry, such as the increase in the energy density and reduction of the battery costs.

Depending on the application, the current traction batteries in the maritime industry are based on either high-energy (HE) or high-power (HP) battery types. The HE batteries are capable of providing long-term continuous nominal power but are less suitable to satisfy the short-term high power demands. On the other hand, the HP batteries are able to handle high power requirements but suffer from energy shortages for a long-term operation. Since in battery technology achieving high power density compromises on the energy density [6], utilizing a single-type battery to comply with the requirements results in a battery system oversized either in energy or power. Hence, the design of the battery system should be based on a balanced compromise between the energy requirement and power demand to reach the most cost-optimal solution. In this respect, a battery hybrid energy storage system (HESS) has been developed, composed of HE and HP battery technologies. The HESS provides an excellent solution to cover a wide range of energy and power requirements that can lead to a lower cost, higher overall efficiency, and longer lifetime in comparison with the monotype battery systems.

Up to the present, many scholars have investigated battery hybridization in electric automotive applications. Some studies have been focused on the integration of Li-ion batteries with supercapacitors [7, 8, 9, 10], while some of them have been focused on the combination of high-energy (HE) Li-ion cells such as NMC and LFP with high-power (HP) cells such as LTO [11, 6, 12, 13]. Although supercapacitors have superior qualities such as high power density and long cycle life, they suffer from a very low energy density compared to Li-ion batteries. This feature limits the application of supercapacitors in electric ships and vessels where high powers are demanded for longer periods. Therefore, for such applications, a HESS based on the combination of HE and HP Li-ion batteries is a feasible option.

This study, for the first time, investigates the optimal sizing and cost assessment of the hybrid battery system based on the integration of HE and HP Li-ion cells for marine applications, considering the required design life of the batteries in the maritime transport sector. In this study, the parallel and cascade full-active HESS topologies are investigated, and the cost of the HESS is compared with the monotype battery topology as the baseline architecture with only HE or HP battery type. The NMC battery type is selected as the HE battery technology, while the HP battery is based on the LTO technology in the present work. This paper is organized as follows. In section 2, the target ship as the use case and the relevant requirements are presented. The architecture of the baseline and considered HESS topologies are given in section 3. In section 4, the sizing procedure including the specifications and lifetime models of the batteries, the dimensioning methodology, and the energy management strategy are discussed. The sizing and cost comparison results are presented in section 5. Finally, the conclusions and future work directions are given in section 6.

II. Target Ship and Requirements

In this paper, a full-electric harbor tug is selected as the target vessel. A harbor tug is a vessel especially designed to

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assist the other vessels during manoeuvres by forcing or tugging them towards the port and also for transporting the floating artifacts from one place to another. Figure 1 shows an electric harbor tug manufactured by DAMEN [14].

The selected tug in this study performs two different jobs and accordingly, operates based on two different load profiles which are known as primary and secondary load profiles. The primary load profile is based on the standard job of the tug, which is performed 3 times per day, leading to 1095 cycles per year. The secondary load profile is related to a heavier job than the standard one which is performed once per week resulting in 52 secondary cycles per year.

Fig.1. Damen RSD-E Tug 2513 [14].

Figure 2 shows the primary and secondary load profiles of the harbor tug. The job performed by the tug boat based on the primary profile takes around 80 minutes, while it takes 190 minutes to fulfill the secondary job. It is worth mentioning that the primary job requires 525 kWh, and 1100 kWh energy is needed for the secondary job. However, the maximum discharge power for both profiles is limited to 3000 kW, and the tug is charged after both standard and heavy jobs at a power of 1000 kW. Three requirements need to be fulfilled for the sizing of the battery system for this application as below:

- The electrical integration of the battery onboard is realized through a fixed DC bus voltage.
- Both HE and HP battery cells operate within the state of charge (SOC) between 90% to 10%.
- The design life of the battery onboard should be 10 years.

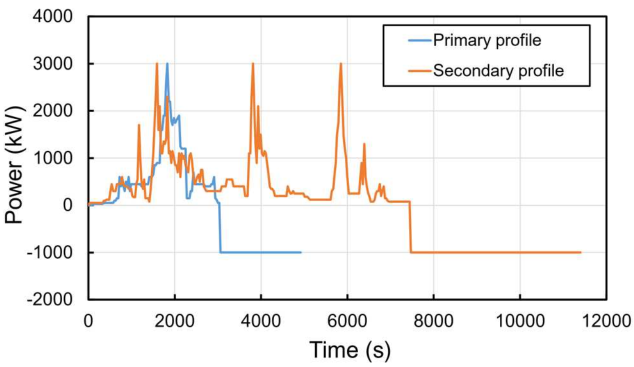


Fig. 2. Load profiles of the harbor tug.

III. Baseline and Hybrid Battery Topologies

A. Baseline Topology

As mentioned earlier, the existing batteries in the marine industry are based on a single-cell topology with either HE or HP cell types. Hence, a monotype battery system is considered as the baseline topology for this application. Due to the fixed voltage requirement at the DC bus, the battery in the baseline topology is connected to a bidirectional DC/DC to decouple the voltage of the DC link from the battery state of charge. Figure 3 shows the schematic of the baseline topology.

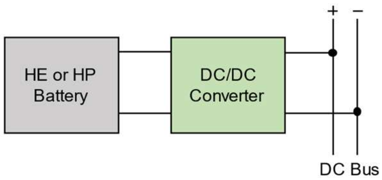


Fig. 3. Baseline battery topology.

B. HESS Topologies

In general, the combination of HE and HP batteries can be realized through different HESS topology configurations. However, a suitable HESS topology for this application must decouple the voltage of the DC bus from both HE and HP battery packs. Hence, the full-active HESS topologies are selected for this application, including HE cascade full-active, HP cascade full-active, and parallel full-active configuration which are shown in Figure 4.

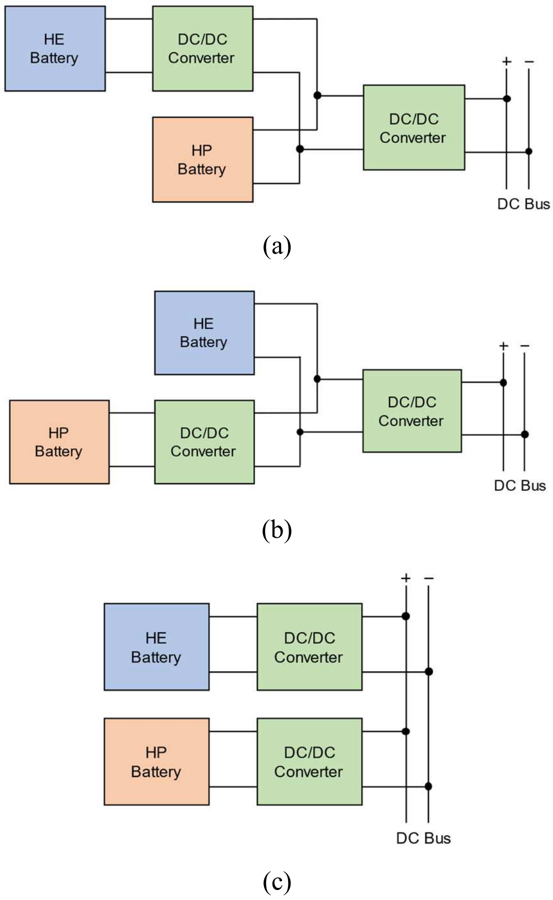


Fig. 4. HESS topologies considered in this work, (a) HE cascade full-active, (b) HP cascade full-active, (c) parallel full-active.

IV. Battery Sizing Procedure

A. Specifications of Batteries and DC/DC Converter

In this work, the lithium nickel manganese cobalt oxide (NMC) and lithium titanate oxide (LTO) chemistries are considered as the HE and HP battery types. Both NMC and LTO are among the common cell technologies already used in electric marine applications. Regarding the DC/DC converter, the cost is assumed to be dependent on the maximum rated power. The electrical parameters of the batteries and the cost of the batteries and DC/DC converter are given in Table 1.

TABLE I. SPECIFICATIONS OF THE BATTERIES AND DC/DC CONVERTER

Parameter	Value	
	HE cell	***HP cell***
Chemistry (-)	NMC	LTO
Capacity (Ah)	50	23
Nominal voltage (V)	3.65	2.3
Charge/Discharge C rate	1/1	4/4
Energy density (Wh/kg)	206	96
Weight (kg)	0.885	0.55
Battery cost (€/kWh)	150	380
DC/DC cost (€/kW)	85	

B. Battery Lifetime Model

The degradation of the Li-ion batteries is characterized by cycle aging and calendar aging. The former is related to the battery capacity reduction while the battery is undergoing cycling. The latter is independent of battery discharge/charge cycles and represents the battery capacity reduction while the battery is not in use. In this work, only the cycle aging of the battery is taken into account. In this respect, the number of cycles that the battery can undergo before reaching the end of life (N_C) can be formulated as [15]:

$$N_C = a \times e^{b \times DOD} + c \times e^{d \times DOD} \quad (1)$$

where DOD is the depth of discharge, which is defined as the usable battery energy to the installed energy and assumed to be a fixed value during the design life of the battery. Additionally, a, b, c, and d are constant fitting parameters. In this study, the number of cycles that battery can undergo before reaching the end of life versus DOD for NMC and LTO battery types is extracted from [16]. Then, the constant parameters are obtained using the least square fitting method by MATLAB. Figure 5 illustrates the fitted curves and the values taken from [16].

C. Sizing Methodology

This section presents the methodology to find the optimal size of the HESS leading to the minimum battery pack cost. Based on the energy conservation principle, the relationship between the power of HE/HP battery packs and the power demanded by the vessel for the primary and secondary load profiles are as follows:

$$\begin{aligned} P_{HE}^{P}(t) + P_{HP}^{P}(t) &= P_{d}^{P}(t) \\ P_{HE}^{S}(t) + P_{HP}^{S}(t) &= P_{d}^{S}(t) \end{aligned} \quad (2)$$

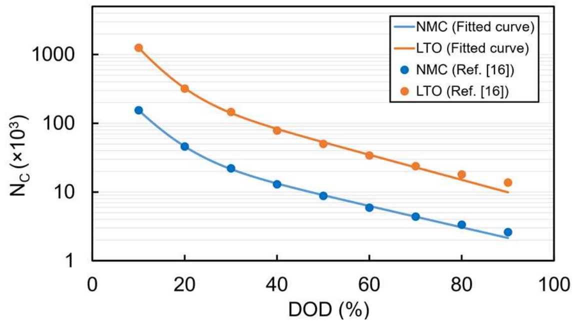


Fig. 5. Number of cycles versus DOD [14].

where $P_{HE}(t)$ and $P_{HP}(t)$ are the power of HE and HP batteries, respectively, and $P_d(t)$ denotes the power demand. The superscripts P and S correspond to the primary and secondary load profiles. It should be noted that the power is positive during the discharge of batteries and negative during the charging process. The usable energy of HE/HP battery packs for the primary profile (E_{usable}^{P}) and secondary profile (E_{usable}^{S}) can be calculated based on:

$$\begin{aligned} E_{usable}^{P} &= \int P_{dis}^{P}(t).dt^{P} \\ E_{usable}^{S} &= \int P_{dis}^{S}(t).dt^{S} \end{aligned} \quad (3)$$

where $P_{dis}(t)$ is the discharge power of the HE/HP battery pack and dt is the time step. Based on the usable energy as well as the installed energy of HE/HP battery pack, the DOD is defined as:

$$\begin{aligned} DOD^{P} &= \frac{E_{usable}^{P}}{E_{ins}} \\ DOD^{S} &= \frac{E_{usable}^{S}}{E_{ins}} \end{aligned} \quad (4)$$

where E_{ins} is the installed energy of the HE/ HP battery pack. Based on the defined DODs and the lifetime model given in section B, the number of cycles that HE/HP battery can undergo before reaching the end of life can be calculated for both primary and secondary profiles (N_C^P and N_C^S). Considering 80% state of health (SOH) of the batteries corresponding to the end of life, and assuming a uniform battery degradation over the time, the percentage of the capacity loss (C_{loss}) of HE/HP battery pack during the design life of the vessel can be calculated as follows:

$$C_{loss} = \left(\frac{N_{design\ life}^{P}}{N_C^{P}} + \frac{N_{design\ life}^{S}}{N_C^{S}} \right) \times 20\% \quad (5)$$

where $N_{design\ life}^{P}$ and $N_{design\ life}^{S}$ are the number of primary and secondary cycles that the batteries need to perform during the design life. As mentioned earlier, for this application a design life of 10 years is required. Therefore, the number of primary and secondary cycles during the design life is calculated as below:

$$\begin{aligned} N_{design\ life}^{P} &= 10950 \\ N_{design\ life}^{S} &= 520 \end{aligned} \quad (6)$$

Four criteria must be met to find the required installed energy for the HE/HP battery packs as follows.

1) The HE/HP battery pack must ensure 10 years of operation before reaching the end of life. To meet this criterion, a minimum installed energy (E_{ins1}) need to be found for each battery ensuring $C_{loss} \leq 20\%$ during 10 years.

2) The HE/HP battery pack must ensure providing the usable energy while the SOC of batteries maintains between 10% to 90% during the design life. Therefore, the installed energy to meet this criterion (E_{ins2}) must satisfy the following equation for HE/HP battery packs:

$$E_{ins,2} - C_{loss} \times E_{ins,2} = \frac{Max(E^{P}_{usable}, E^{S}_{usable})}{0.8} \quad (7)$$

3) To ensure that the input current to the HE/HP cell during the charging process doesn't exceed the maximum charge current of the cell given in the datasheet (Table 1).

$$E_{ins,3} = \frac{Max(P^{P}_{ch}, P^{S}_{ch}) \times Cap_{cell}}{I_{ch,cont}} \quad (8)$$

where P^{P}_{ch} and P^{S}_{ch} are charging power of the HE/HP pack for primary and secondary profiles, Cap_{cell} is battery capacity, and $I_{ch,cont}$ denotes the continuous charging current of the HE/HP cell.

4) To ensure that the output current of the HE/HP cell during the discharging process doesn't exceed the maximum discharge current of the cell given in the datasheet (Table 1).

$$E_{ins,4} = \frac{Max(P^{P}_{disch}, P^{S}_{disch}) \times Cap_{cell}}{I_{disch,cont}} \quad (9)$$

where P^{P}_{disch} and P^{S}_{disch} are discharging power of the HE/HP pack for primary and secondary profiles, and $I_{disch,cont}$ denotes the continuous discharging current of the HE/HP cell.

Finally, the capacity to be installed for HE/HP battery types while meeting all the above criteria is found as:

$$E_{ins} = Max\left(E_{ins,1}, E_{ins,2}, E_{ins,3}, E_{ins,4}\right) \quad (10)$$

and the HESS cost is calculated by:

$$Cost_{HESS} = E_{ins,HE} \times Cost_{HE} + E_{ins,HP} \times Cost_{HP} + Cost_{DC/DC} \quad (11)$$

D. Energy Management Strategy

A rule-based energy management method is employed for power sharing between the HE and HP battery packs. The HE battery type is considered as the primary energy source for providing power for the ship. In this regard, a power threshold ($P_{max,HE}$) is defined for the HE battery as the maximum power that HE battery can supply. As long as the power demanded by the vessel is less than the power threshold, only HE battery supplies the required power. When the power demand is beyond this threshold, HP battery supplies the additional required power. Figure 6 illustrates the rule-based energy management of the HESS. It must be mentioned that the same energy management strategy is applied for both primary and secondary profiles.

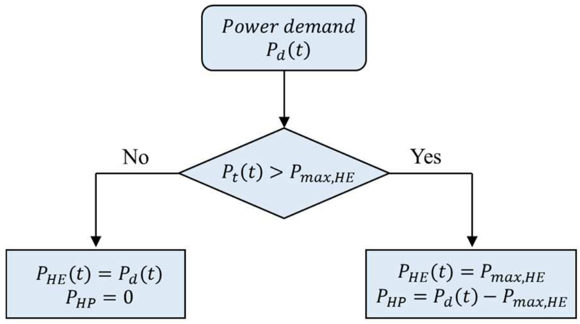


Fig. 6. Rule-based energy management strategy.

Figure 7 shows the flowchart of HESS sizing and cost assessment at different values of power threshold ($P_{max,HE}$). As it is observed from Figure 7, the required energy to be installed and accordingly, the HESS cost is calculated for 1 kW intervals of $P_{max,HE}$. It should be noted that $P_{max,HE} = 0$ refers to the baseline topology with HP cell, and $P_{max,HE}$=$Max(P_d)$ shows the baseline with HE cell type. In this work, the sizing of the battery is performed by MATLAB scripting.

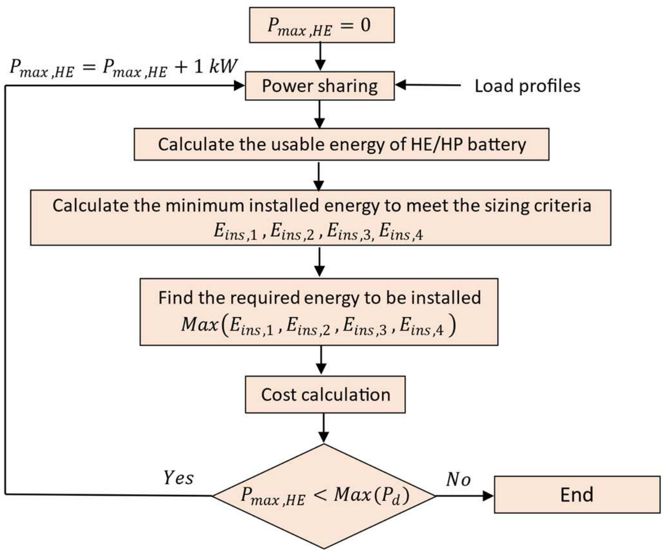
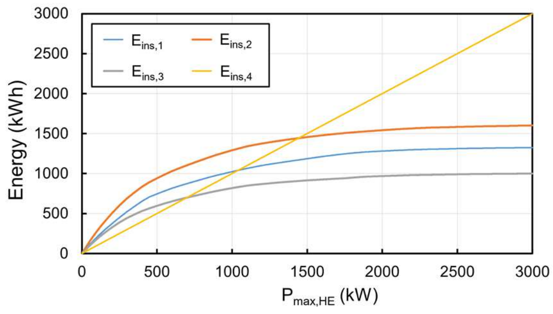


Fig. 7. Sizing and cost assessment flow chart.

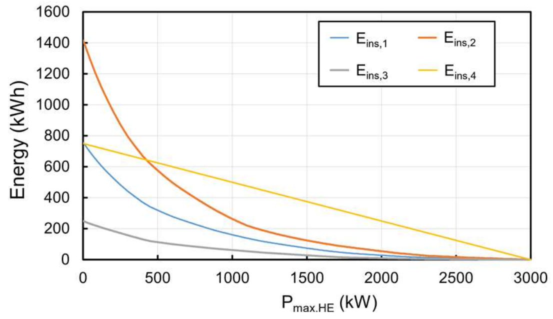
V. Results and Discussion

This section presents the battery sizing and cost analysis results. Figure 8(a) and 8(b) show the required installed energies to satisfy the requirements for the HE and HP battery type including $E_{ins,1}$, $E_{ins,2}$, $E_{ins,3}$ and $E_{ins,4}$ versus $P_{max,HE}$. As expected from the energy management strategy, increasing $P_{max,HE}$ leads to an increase in the amount of installed energies for the HE battery, while it has a reverse influence on the installed energies for HP battery type.

For both HE and HP battery pack, depending on the $P_{max,HE}$, $E_{ins,2}$ and $E_{ins,4}$ have the biggest influence on the required install energy. As can be observed in Figure 8(a), for the HE battery, the size of the installed energy is dictated by $E_{ins,2}$ for the power thresholds of $P_{max,HE} \leq 1442$, while for the $P_{max,HE} \geq 1442$ the installed energy is dictated by $E_{ins,4}$. For HP battery, the installed energy is dictated by $E_{ins,2}$ and $E_{ins,4}$ for the power thresholds of $P_{max,HE} \leq 425$ kW and $P_{max,HE} \geq 425$ kW, respectively.



(a)



(b)

Fig. 8. Energy to be installed to meet the design criteria, (a) HE battery (b) HP battery.

Figure 9 depicts the cost of the baseline, and the investigated HESS topologies versus $P_{max,HE}$. As it is seen, the HESS with parallel full-active topology results in a lower cost than the other topologies for all values of $P_{max,HE}$. A certain $P_{max,HE}$ is found for the parallel and HE cascade topologies leading to the minimum cost, while for the HP cascade topology, the HESS cost always reduces with an increase in $P_{max,HE}$. The minimum cost of the parallel, and HE cascade topologies corresponds to the power threshold of $P_{max,HE} = 1442\ kW$ and $P_{max,HE} = 425\ kW$, respectively.

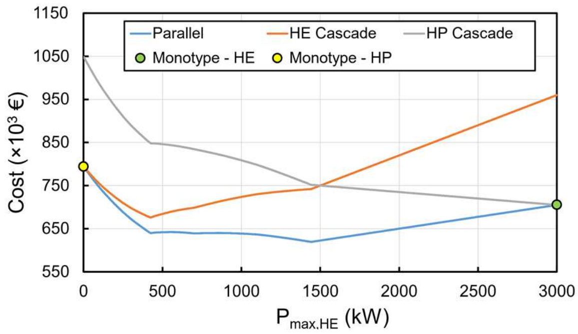


Fig. 9. Cost of monotype and HESS topologies at different values of $P_{max,HE}$.

Figure 10 illustrates the optimal cost of the all investigated topologies. As expected from Figure 9, the highest cost corresponds to the baseline topology with HP battery cell, and the minimum cost is gained by a parallel full-active HESS topology. For this case, the installed energy of NMC battery is 1442 kWh, and 389 kWh need to be installed for HP battery. Moreover, the installed energy for the baseline with HE cell is 3000 kWh, while for the baseline with HP cell the installed energy is 1415 kWh. The results show that the parallel full-active HESS reduces the cost of the battery system for this harbor tug by 28% compared to a monotype LTO battery pack, and around 14% compared to the baseline with NMC cell.

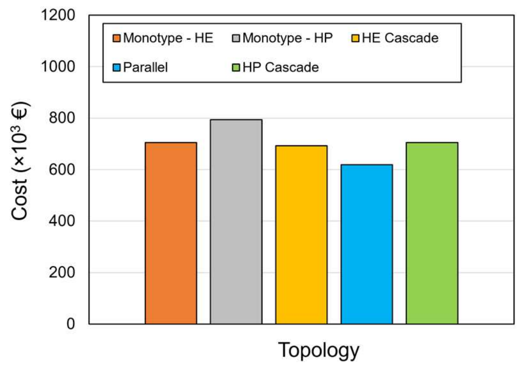
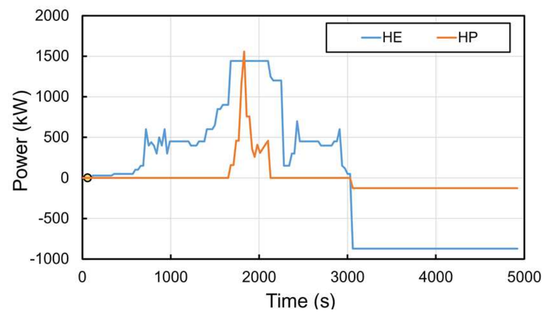
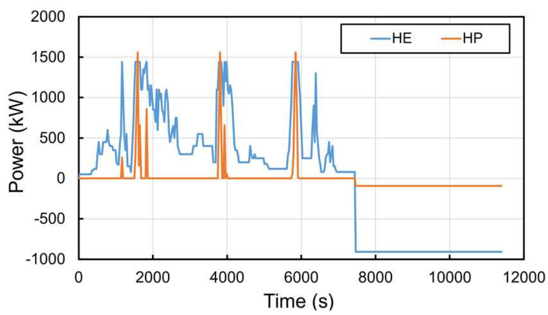


Fig. 10. Optimal battery pack cost.

Figure 11 shows the optimal power sharing between the HE and HP battery packs for the primary and secondary load profiles for parallel full-active topology. It is seen that the HE battery is responsible for providing most of the demanded power, and the role of the HP battery is to assist the HE battery during the peak powers. Consequently, the amount of required energy for the primary cycle provided by the HE battery is 458 kWh, and it is 67 kWh for the HP battery. Regarding the secondary cycle, the energy provided by HE and HP battery types are 998 kWh and 103 kWh, respectively.



(a)



(b)

Fig. 11. Optimal power sharing between HE and HP battery pack for parallel full-active topology, (a) Primary profile, (b) Secondary profile

VI. Conclusion

A sizing analysis and cost assessment is performed on the full-active HESS topologies for a harbor tug. In this respect, the NMC and LTO battery types are selected as the HE and HP batteries within the HESS. Employing a rule-based energy management method, the cost of the HESS is compared to the baseline battery topology with monotype cell chemistry. The design life of the battery is considered to be 10 years, and the batteries operate within the 90% to 10% SOC. The parallel full-active HESS results in the lowest cost among all the investigated topologies requiring 1442 kWh and 389 kWh energy to be installed for the HE and HP batteries, respectively. A monotype battery based on HE cell type requires 3000 kWh energy to be installed, while 1415 kWh is needed for the monotype topology with HP cell type. The cost comparison results indicated that the optimal parallel full-active HESS battery pack leads to 28% cost reduction compared to the monotype battery pack with HP cell, and 14% lower cost compared to the monotype battery pack with HE cells.

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