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This is an “Accepted article” version of a paper and it is not the final version as appearing in the Proceedings of the “63º Congreso De Ingeniería Naval E Industria Marítima” CIIN 2024 (ISBN: 978-84-126751-4-6).

How to Cite this article:

Marcos Blanco, Jorge Nájera, Gustavo Navarro, Eduardo Rausell, Valentin Urda, Marcos Lafoz “DIMENSIONING METHODOLOGY OF A HYBRID ENERGY STORAGE SYSTEM ON-BOARD VESSELS” 63º Congreso De Ingeniería Naval E Industria Marítima CIIN 2024 (2024).

THIS WORK WAS DEVELOPED UNDER THE FINANCIAL SUPPORT OF THE PROJECT POSEIDON (ID: 101096457), WHICH HAS RECEIVED FUNDING FROM EUROPEAN UNION'S HORIZON EUROPE RESEARCH AND INNOVATION PROGRAM UNDER HORIZON.2.5.7 - CLEAN, SAFE AND ACCESSIBLE TRANSPORT AND MOBILITY AND HORIZON.2.5.6 - INDUSTRIAL COMPETITIVENESS IN TRANSPORT (HORIZON-CL5-2022-D5-01-02).



DIMENSIONING METHODOLOGY OF A HYBRID ENERGY STORAGE SYSTEM ON-BOARD VESSELS

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RESUMEN

La progresiva electrificación de los transportes marinos ha originado la instalación de sistemas de almacenamiento de energía en buques para alimentar los sistemas de tracción eléctricos. Las baterías de ion-litio son la tecnología más utilizada. Sin embargo, para aplicaciones de transporte marino con perfiles de consumo eléctrico que tienen grandes picos de potencia durante unas pocas veces en un día, las baterías pueden no ser la opción más adecuada tecno-económicamente, debido a su envejecimiento. En este sentido, la hibridación de baterías con los sistemas de almacenamiento de respuesta rápida como los supercondensadores puede ser más conveniente, alargando la vida útil de la batería con la consecuente reducción de coste. Este trabajo, enmarcado dentro del Proyecto POSEIDON (Horizon Europe, G.A. nº101096457), presenta un primer análisis con datos de consumo reales en el que se estudia tecno-económicamente la conveniencia de instalar stacks de supercondensadores en un ferry en el que ya existe una batería. Los resultados muestran que, cuando ya se dispone de una batería, instalar supercondensadores no compensa económicamente. En un segundo análisis se estudia la tecno-económicamente la conveniencia de instalar stacks de supercondensadores para reducir el tamaño de la batería, esto es, redimensionar el sistema híbrido y cambiar la proporción de baterías y supercondensadores. Los resultados muestran que, en una etapa previa de dimensionado, sí que es beneficioso tecno-económicamente el uso de un sistema híbrido de baterías de ion-litio y supercondensadores.

ABSTRACT

The ongoing electrification of marine transport has led to the installation of energy storage systems on vessels to power electric traction systems. Lithium-ion batteries are the preferred technology. However, for marine transportation applications with electrical consumption profiles that have large power peaks for a few times in a day, batteries may not be the most suitable option techno-economically, due to their aging. In this sense, the hybridization of batteries with fast response storage systems such as supercapacitors may be more convenient, extending their lifespan with the consequent reduction in cost. This work, framed within the POSEIDON Project (Horizon Europe, G.A. nº101096457), presents a first analysis with real consumption data in which the convenience of installing supercapacitor stacks on a ferry in which there is already a battery is techno-economically studied. The results show that, when a battery is already available, installing supercapacitors does not pay off economically. In a second analysis, the techno-economic convenience of installing supercapacitor stacks to reduce the size of the battery is studied, that is, resizing the hybrid system and changing the proportion of batteries and supercapacitors. The results show that, in a previous sizing stage, the use of a hybrid system of lithium-ion batteries and supercapacitors is indeed beneficial techno-economically.

1. INTRODUCTION

1.1. Li-ion batteries as a key actor for the electrification of maritime transport

The sector of maritime transport is suffering a progressive electrification, mainly driven by specific European regulations and internal policies of shipping companies [1],[2]. This ongoing electrification process is primarily focused on diminishing the carbon dioxide emissions on all kind of vessels, which implies substituting the traditional diesel engines for non-polluting power sources. Given the inherent nature of a vessel, which transports means and/or passengers between harbors, portable electric power sources in form of energy storage systems are the most appropriate solution.

Among the different energy storage technologies, Li-ion batteries energy storage systems (Li-BESSs) are the most accepted ones given their high energy density, reasonable power density, fast response time, and a continuously falling purchasing cost in terms of \$/kWh [3]. In this sense, previous studies in electrifying vessels through Li-BESSs integration have proven to be successful, as stated in [4], where a hybrid system with diesel engines and Li-BESS achieves the highest CO₂ reduction among the studied configurations. Authors in [5] analyzed the Life-Cycle Assessment (LCA) and the Life-Cycle Cost Assessment (LCCA) of different powering solutions in a short-sea navigation ship, outcoming that electrifying with a Li-BESS is the most appropriate alternative according to environmental and economic indicators. A similar approach has been followed in [6], comparing five Li-BESS solutions and three marine diesel oils, finding out that lithium iron phosphate (LFP) Li-BESS is the preferred solution for powering the selected passenger vessel according to the indicators. Aside from studies that analyze the convenience of including a Li-BESS for electrifying vessels, other related areas such as energy management control have been getting attention, as in [7], where different energy management strategies are studied for reaching an efficient and cost-effective power scheduling in zero-emissions ferry ships with Li-BESSs.

Based on the works referenced in the previous paragraph, among others, Li-BESSs seem to be one of the key actors for decarbonizing the maritime transport sector. However, it is well known that Li-BESSs suffer from aging, which implies that both their energy storage capacity and power diminish due to the exposure to ambient conditions and passage of time, and to the cycling conditions during charge/discharge processes [8]. This drawback becomes significantly relevant in a maritime environment with humidity, salt, and severe temperature changes. Besides, the typical power demand profile of passenger vessels, ferries, and short-sea navigation ship include peaks of several times the nominal power of the battery during operations in harbor, i.e. docking maneuver in port, which happen a considerably high number of times along a day and foster the cycling aging.

Several alternatives have been proposed in the literature for expanding the lifetime of an on-board Li-BESS, delaying the needs for replacing it and, hence, improving the economical indicators and the revenue obtained from its installation. The most promising solutions verse about including one or more energy storage system (ESS) together with the Li-BESS, having a hybrid energy storage system (HESS).

1.2. HESS overview for on-board integration

Previous works in hybridizing Li-BESSs in vessels have considered doing it with fuel cells, supercapacitors (SCs) and/or kinetic energy storage systems (KESSs) such as flywheels. Both SCs and KESSs are part of a larger ESS group named fast response energy storage systems (FRESSs), which account for a high power density, fast response time in the range of milliseconds, and very low aging [3]. The main drawback is that, commonly, their energy density is reduced. In this sense, given the complementary characteristics between Li-BESSs and FRESSs, hybridizing them in vessels for electrifying it and covering the power demand, while preventing the Li-BESS from suffering an excessive aging seems to be promising.

The authors in [9] developed an energy flow control and sizing methodology of a Li-BESS and SCs HESS, achieving a better efficiency when compared to a Li-BESS vessel, and reducing both ESS sizes. A coordinated control for a HESS formed by SCs and a Li-BESS is developed in [10], improving considerably the fast response of the HESS in sudden power demand situations. For KESSs, the authors in [11] proposed two control algorithms for a HESS formed by a Li-BESS and a KESS, outperforming the baseline control in terms of power fluctuation mitigation and HESS power-loss reduction.

As seen in the previous paragraph, the aforementioned studies are focused on including another ESS together with the Li-BESS in a designing stage, i.e. prior to the installation of the HESS in a vessel. The work presented in this paper analyzes, on one hand, the convenience of including a set of SCs in a vessel where there is already a Li-BESS, so it is already sized, and presents the techno-economic results when aiming to reduce the aging of the Li-BESS while covering the vessel demand during maneuvers on port. The analysis makes use of data taken from Balearia's real ferry ship. On the other hand, this work includes a study to compare different sizes of the HESS (SCs and Li-BESSs) for the use case of Balearia, to analyze what is the Li-BESS size at where it is techno-economically beneficial to include SCs to prevent the Li-BESS from an excessive aging, while dealing with the power demand during maneuvering on port.

Section 2 includes the description of the models and the use case, while Section 3 and Section 4 include the results from the two analyses. Conclusions are drawn in Section 5.

2. USE CASE & MODELS

2.1. Vessel consumption

The selected vessel consumption for the use case is the one measured the 29th of September 2023 by the Battery Management System (BMS) of the Li-BESS mounted in Balearia's ferry ship. Balearia's internal policy states that during maneuvers on port no diesel engine should be in operation, and all consumptions must be covered by the Li-BESS. Besides, during the trip the diesel engine powers the vessel and charges the battery. During the night there is no power flowing through the Li-BESS. The Li-BESS power profile is depicted in Fig. 1.

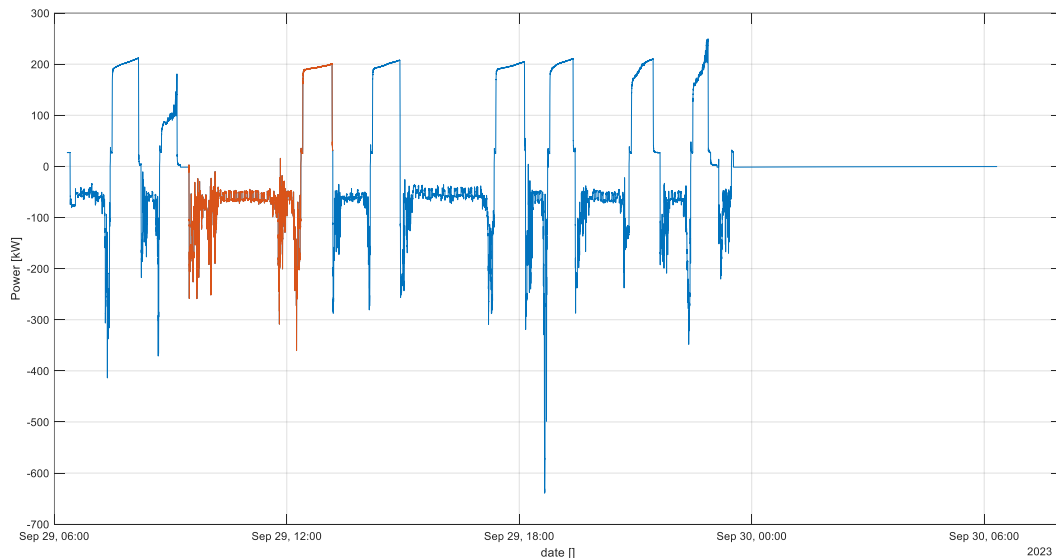


Fig. 1. Power profile of the Li-BESS for the Balearia's ferry ship.

Fig. 1 shows the power delivered (negative) or charged (positive) during a set of 8 trips. The Li-BESS is discharged during maneuvers on port, and docking and undocking operations are clearly noticeable, since they account for the higher discharge peaks. Moreover, the Li-BESS charges with a constant current when the vessel leaves the port (the charging power increases slightly as the Li-BESS gets charged because of the consequent voltage increment).

For sake of simulation speed, the cycle highlighted in red has been selected as the most representative one.

The results shown in the following sections are based on a consumption cycle formed by that single cycle repeated eight times along a day.

2.2. HESS topology & control

To deal with the power consumed by the vessel during maneuvers on port as well as reducing the Li-BESS aging, several topologies for hybridizing Li-BESS with SCs can be considered [12]. Out of the 8 topologies considered in [12], the “Two Stage SCs / Batteries” topology is the most straightforward for a vessel that already equips a Li-BESS, since it comprises the addition of an extra DC/DC converter, the SCs can operate in a wide voltage range (75% of their capacity), and the DC-link voltage is imposed by the battery. Hence, the current/power delivered/charged by the SCs is the controllable variable. Fig. 2 shows a scheme of the HESS topology.

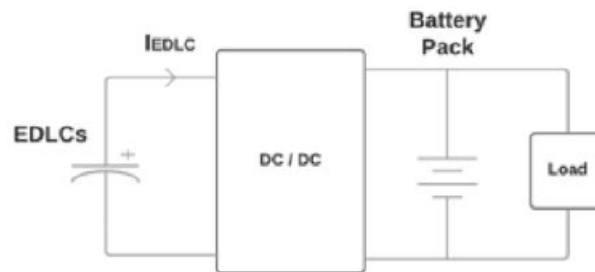


Fig. 2. Selected HESS topology for the Use Case [8].

There is no evident way on how to control a HESS system like the one proposed in Fig. 2. However, and given that the objective of this work is powering the vessel with the HESS while reducing the Li-BESS aging, a filtering control has been selected. Thus, the vessel's power demand will be filtered, so the Li-BESS will cope with that power and energy, while the SCs will cover the difference between the real power curve and the filtered one. In this way, for covering high power peaks of short duration the Li-BESS will have the assistance of the SCs, reducing the associated aging. During the charging process, the Li-BESS will charge at its maximum ($SoC = 100\%$) so it is guaranteed that there will be enough energy for the following cycle.

For the selected Use Case, the Li-BESS power and energy has 35 stacks of 468.1kW and 23Ah. The SCs size will vary depending on the filter time constant, i.e. the larger the time constant of the filter, the higher the number of SC stacks since they must deal with more energy. Each SC stack accounts for 127.2kW and 0.001873kWh.

2.3. Li-BESS model

The Li-BESS model is based on the work developed in [8]. This model is based on the well-known Shepherd model and on [12], which describes the electrochemical behavior in terms of voltage, current, internal resistance and SoC.

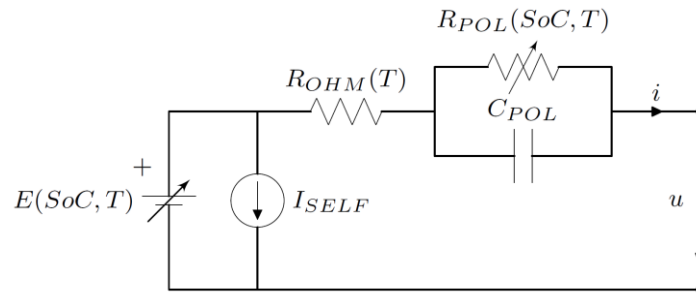


Fig. 3. Li-BESS model proposed in [8].

The model accounts for three sub-models: a voltage/runtime model, a thermal model, and an aging model. The thermal model comprises generation and evacuation modules, and the aging model includes both cycling and calendar aging, the former dependent on the cell temperature, rate of charge/discharge (C_{rate}) and Ah throughput, and the latter on the cell temperature, SoC, and time.

Further and detailed explanation of the model, equations, parameters, and influencing variables can be found in [8].

2.4. SC model

The SC model is based on the work developed in [13]. The model includes the frequency response of 2 SC cells connected in series and their equalization circuit. Moreover, this model allows for an straightforward extrapolation to stacks with several cells connected in series.

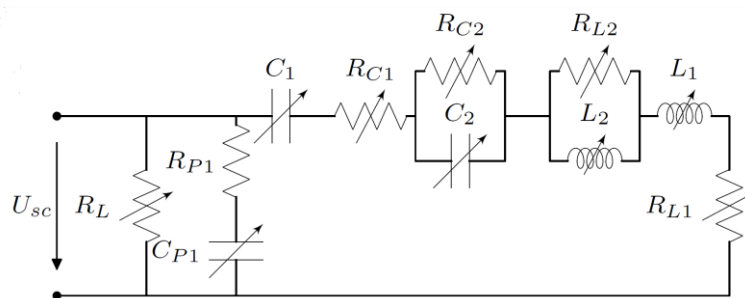


Fig. 4. SC model proposed in [13].

In the scheme shown in Fig. 4 the variable elements are SoC dependent. The SCs model follows a similar approach as the Li-BESS one, and includes a thermal sub-model formed by a generation and evacuation modules. Further and detailed explanation of the model, equations, parameters, and influencing variables can be found in [13].

2.5. Simulation methodology

Simulations have been performed with MATLAB Simulink, using the power profile described in Section 2.1, the HESS topology and control from Section 2.2, and the Li-BESS and SC models from Sections 2.3 and 2.4 respectively.

For performing the techno-economic analysis, Li-BESS and SCs costs (including power converters) have been obtained from [14] and [15].

Simulations are run for the selected cycle on a 0.1 second basis, and several assumptions have been taken by the authors:

- The DC/DC converter is assumed ideal.
- For computing the aging, the State of Health (SoH) is not fed back, so parameters are not influenced by changes in the SoH. This may be important when computing the SoC since it will be varying according to the maximum capacity of the Li-BESS.
- A SoH of 80% have been considered for replacing the Li-BESS.
- Costs may vary depending on the market and sector, and no annual discount rate or capital recovery factor has been taken into consideration for the economical results.
- The results have been calculated for a project of 25 years of life assuming 8 complete trips/day.

3. ANALYSIS 1: SC FOR REDUCING THE AGING IN AN EXISTING LI-BESS

3.1. Analysis 1: methodology

As mentioned in the previous sections, this first analysis verses about hybridizing an existing Li-BESS with SCs in a Balearia's ferry ship, covering the consumption while the vessel is on port, and aiming to reduce the aging suffered by the Li-BESS. It is expected that the aging suffered by the Li-BESS diminishes with respect to the no-HESS case, but it is not straightforward if this technical improvement will also translate into an economical benefit, given that reducing the Li-BESS aging implies delaying the time required for replacing it, and hence a higher economic benefit along the project lifetime.

To perform this study, a set of simulations have been performed, changing the time constant of the filter. In this sense, a low time constant implies that the Li-BESS will have to deal with more

energy, having a low contribution from SCs, while the SCs will have a greater contribution for higher time constants.

The number of stacks of SCs have also been varying along the simulations, given that a low number of stacks is not compatible with a high time constant, since the SCs will be discharged in a short time and the Li-BESS will have to deal with the whole power demand, and thus not being able to follow the filtered power curve.

3.2. Analysis 1: results

Fig. 5 shows the studied combinations of SCs and filter time constant. For all the combinations, the error between the power required by the vessel and the power delivered by the SCs and the Li-BESS (filtered power curve) is calculated and highlighted in red in Fig. 5. For the Analysis 1, the combinations of SC stacks and filter time constant that account for errors lower than $1e-05$ are the ones located at the right of the non-dashed red line in Fig. 5. Those are the combinations that will be considered for the analysis since they allow the HESS to cover the vessel's demand. As expected, combinations of low number of SC stacks and high filter time constant induce errors above $1e-05$ and are not considered for the analysis.

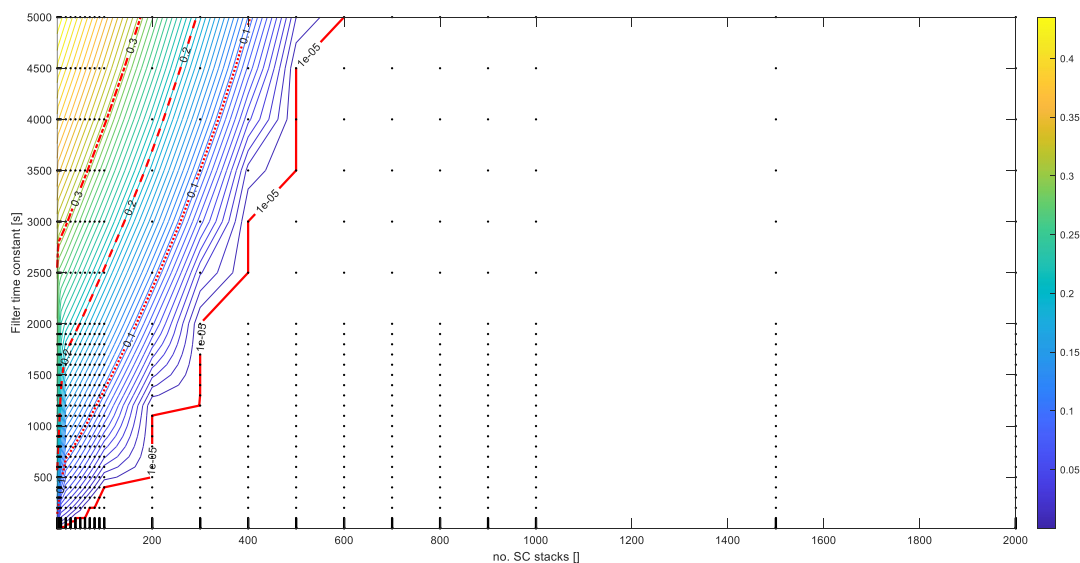


Fig. 5. Analysis 1: power error (P required vs. P delivered)

Fig. 6 and Fig. 7 complete the information derived from the simulations.

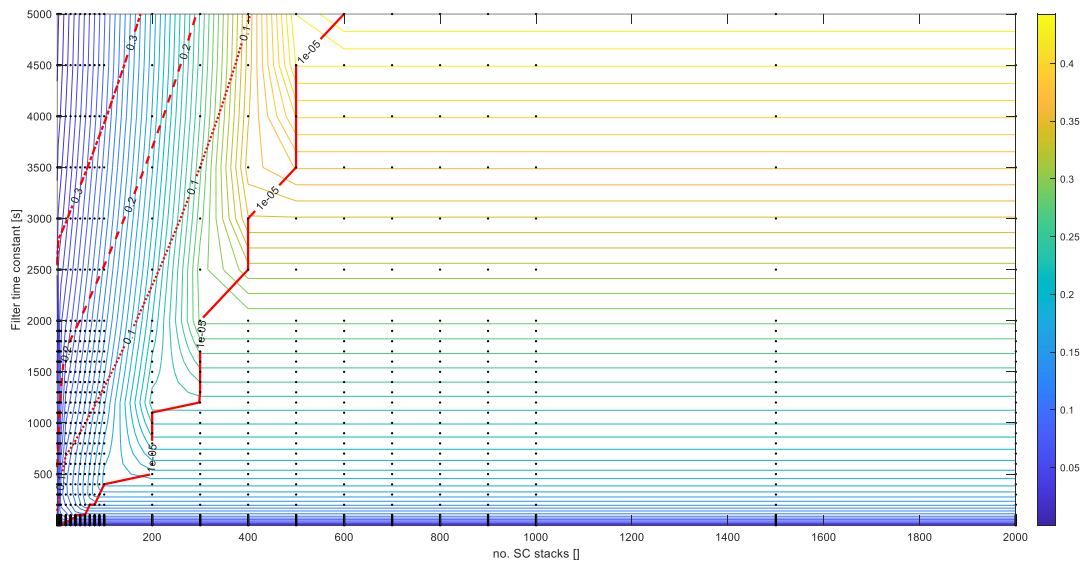


Fig. 6. Analysis 1: Percentage of the power provided by SCs.

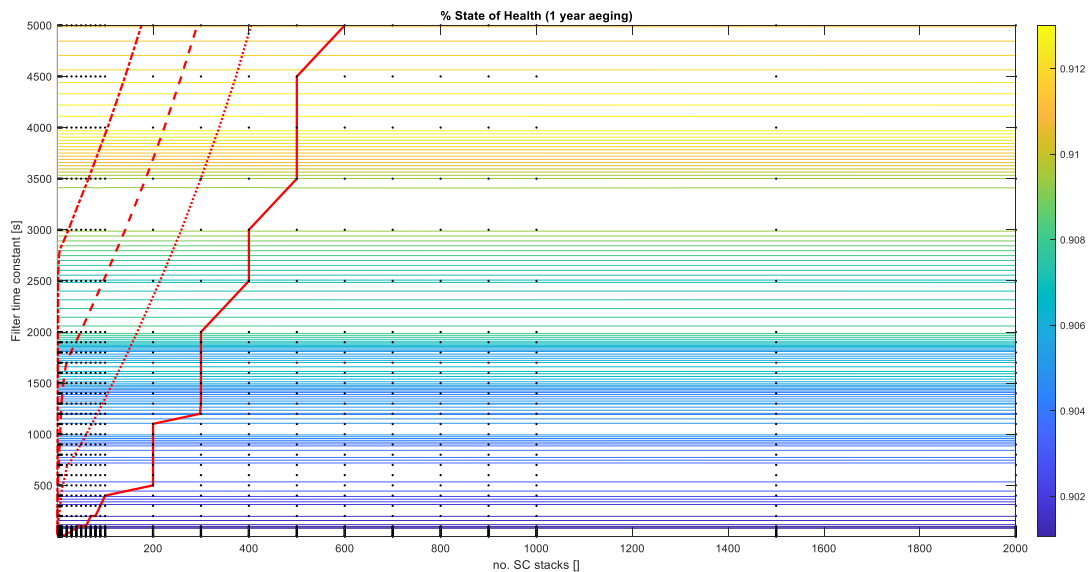


Fig. 7. Analysis 1: Li-BESS SoH after 1 year.

From a technical perspective, increasing the time constant of the filter increments the participation of the SCs, reaching a maximum of 45% of the power, as seen in Fig. 6.

As expected, this higher participation of the SCs results in a lower aging for the Li-BESS, since the cycling aging is diminished because of the C_{rate} reduction. It is noticeable that the Li-BESS is suffering a great aging independently of the SC stacks and filter. This occurs because of the calendar aging, which remain constant for all scenarios. For this particular use case, the calendar aging is responsible for most of the aging, since the Li-BESS is forced to be at 100% SoC during most of the time along a day, suffering an extra aging that could be avoided if it is kept at a different SoC (which would imply implementing a different control than the one proposed for this work). From the simulations, differences in aging between different filter time constants are no greater than 15%, as seen in Fig. 7, and those are the differences that the SCs can diminish by reducing the cycling aging in the Li-BESS.

Having this in mind, it seems not economically viable to introduce SCs in a HESS with Li-BESS, since the reduction in aging will lead to fewer repositions, but the investment in SCs does not compensate for it. This is better seen in Fig. 8, which shows the investment and cost saving lines for the HESS as the SC stacks increase. Given that they never cross each other, it means that there is not a scenario where including SCs induces a higher saving in cost than the investment required to include those SCs. Notice that the cost saving line is slightly increasing, but far from the increasing rate of the investment line.

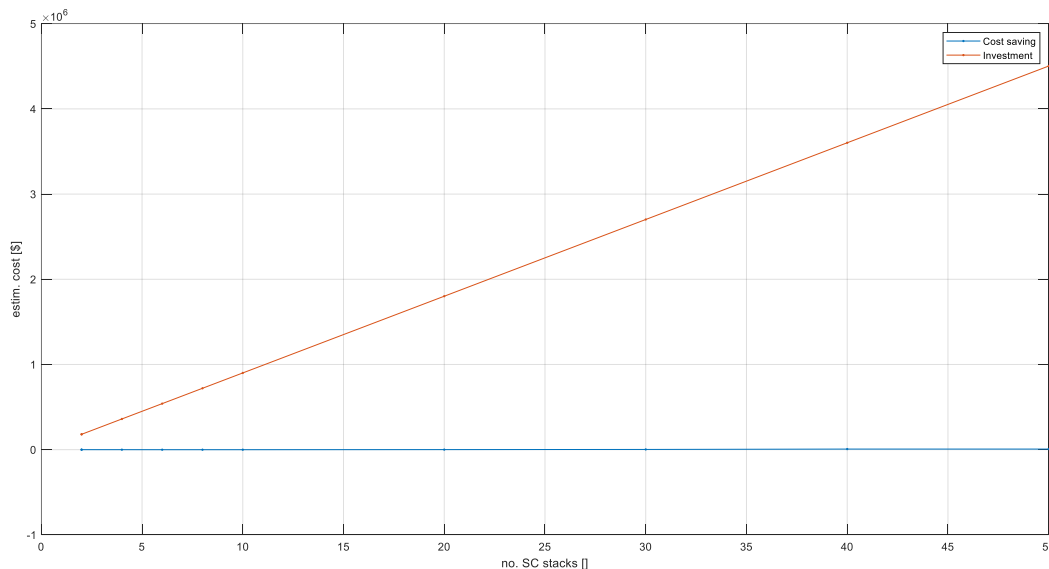


Fig. 8. Analysis 1: cost saving vs. investment.

4. ANALYSIS 2: SC FOR REDUCING THE AMOUNT OF LI-BESS

4.1. Analysis 2: methodology

Starting from the results of the previous analysis, this second analysis aims to re-dimension the HESS, so it is economically viable. In this new scenario, the objective is slightly modified. As happened in Analysis 1, the HESS still needs to cover the vessel's power demand, but 6 different Li-BESS configurations are tested, each one combined with the same set of SC stacks analyzed in the previous section. Hence, the SCs are not reducing the stress (C_{rate}) of the Li-BESS so its aging is diminished, but they are replacing the Li-BESS units, so the resultant HESS is better optimized in terms of power and energy and is techno-economically feasible.

The Li-BESS considered in Balearia's ferry ship accounts for 35 Li-BESS stacks (or modules). Thus, as the number of SC stacks increases, the optimum number of Li-BESS modules will be decreasing. The 6 different Li-BESS modules tested for Analysis 2 are: 35, 30, 25, 20, 15, and 13. For each of them, a complete set of simulations for different SC stacks is performed.

4.2. Analysis 2: results

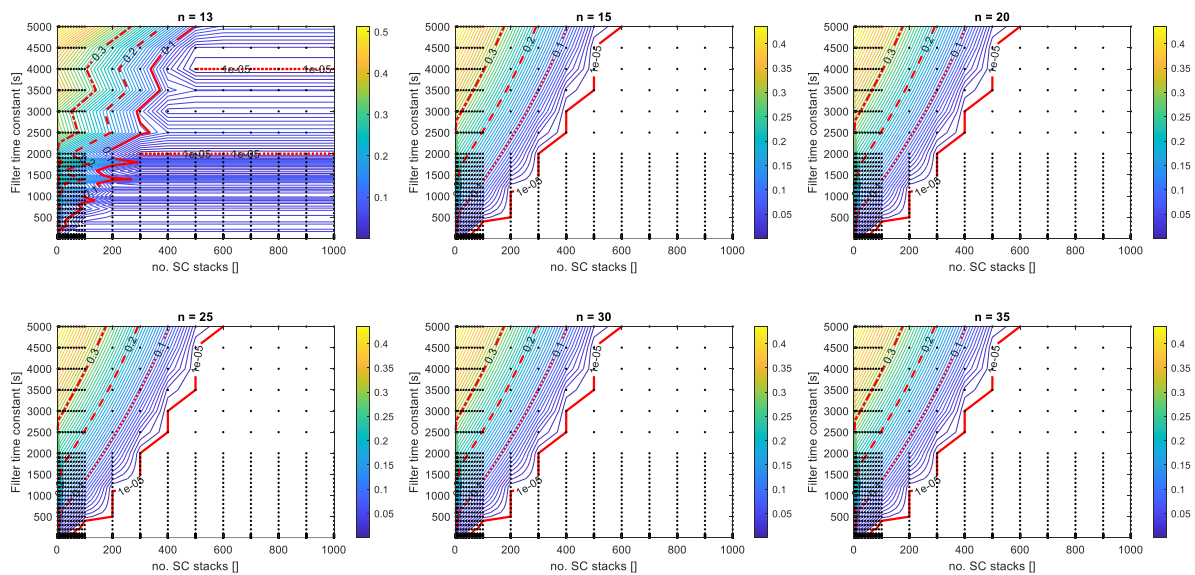


Fig. 9. Analysis 2: power error (P required vs. P delivered) for different Li-BESS stacks.

Fig. 9 shows the set of valid HESS for each combination of Li-BESS modules and SC stacks. As happened in Analysis 1, all combination of values located at the right of the non-dashed red line (errors below $1e-05$) are considered for the analysis. No difference is observed for modules $n = 35$ to $n = 15$, but at $n = 13$ the number of valid combinations is much lower.

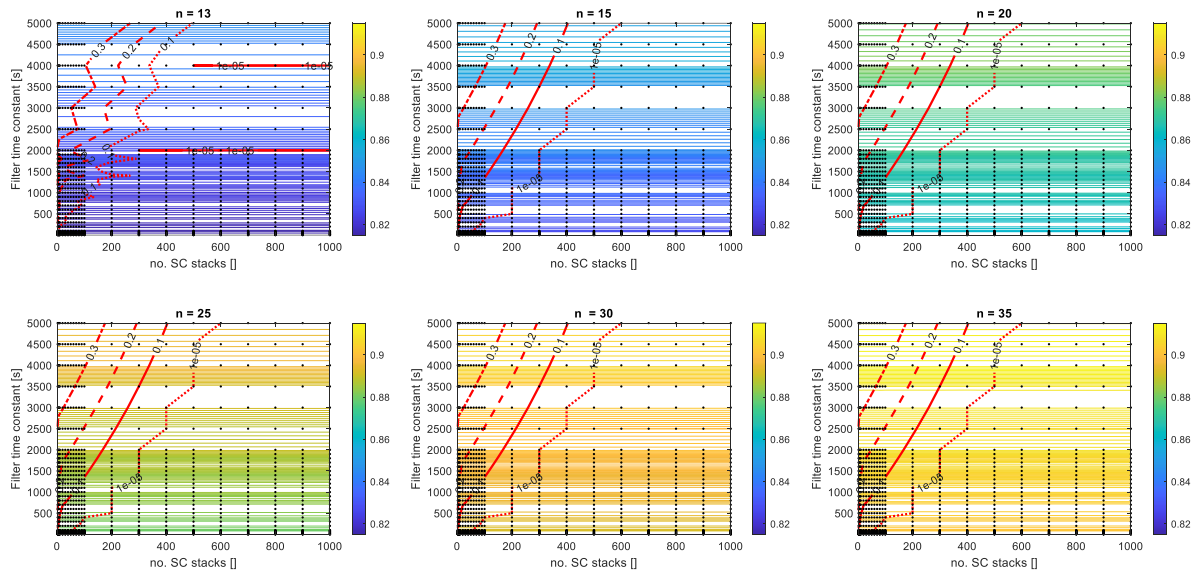


Fig. 10. Analysis 2: Li-BESS SoH after 1 year for different Li-BESS stacks.

Fig. 10 shows the SoH of the Li-BESS after 1 year for the different HESS configurations. The general trend indicates that the aging increases as the number of Li-BESS modules decreases ($n = 35$ suffer less aging than $n = 13$), and the lower the filter time constant, the higher the aging (since the Li-BESS must deal with a higher part of the consumption because it is less filtered).

At last, the techno-economic viability of the different HESS is shown in Fig. 11. The cost investment line (due to the inclusion of SCs) is the same from Analysis 1, and 6 other lines are included from $n = 30$ to $n = 10$, considering the savings due to the reduction of the Li-BESS aging in addition to the reduction of Li-BESS modules. The figure shows that decreasing the number of Li-BESS modules as the number of SCs modules increases can be beneficial also from an economic point of view, having all the scenarios (from $n = 30$ to $n = 10$) combinations of HESS (Li-BESS + SCs) where the investment cost remains below the savings for replacing Li-BESS units with SCs. As seen in the image, a Li-BESS with 10 modules allows for the highest savings. For the presented use case, a lower number of Li-BESS modules could not be possible since the cycle of the vessel could not be completed.

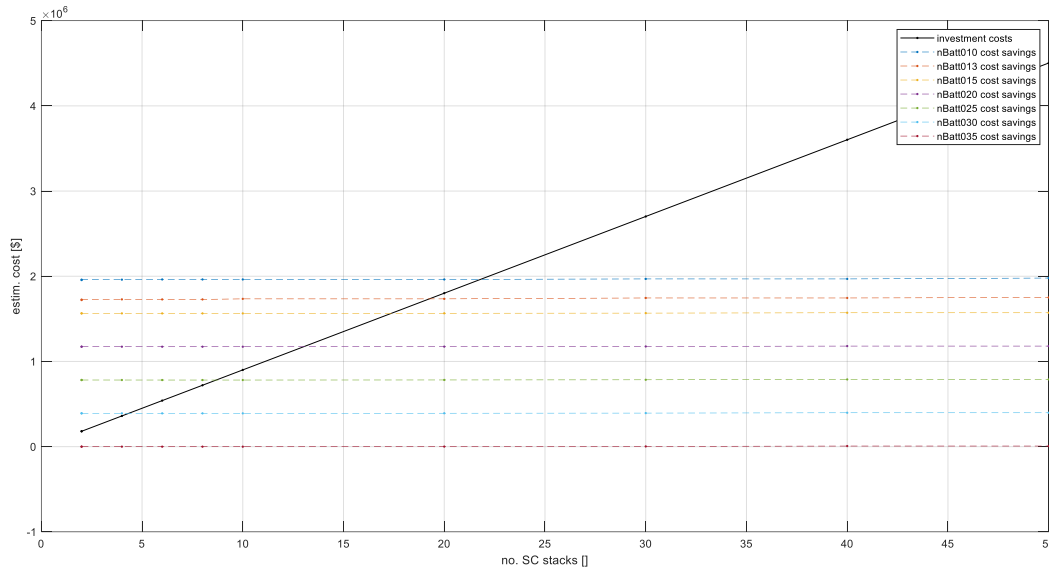


Fig. 11. Analysis 2: cost saving vs. investment for different Li-BESS stacks.

5. CONCLUSIONS

This work, framed within the POSEIDON Project (Horizon Europe, G.A. n°101096457), presents two analysis using real consumption data from a Balearia's ferry ship: a first analysis in which the convenience of installing supercapacitor stacks on a ferry in which there is already a battery is techno-economically studied, and a second analysis where the techno-economic convenience of installing supercapacitor stacks to reduce the size of the battery is studied, that is, resizing the hybrid system and changing the proportion of batteries and supercapacitors.

Results show that for vessels where there is already a Li-BESS in use for traction purposes, hybridizing it with a FRESS (SCs in particular) may not be feasible from a techno-economic point of view. Including SCs in the HESS helps in reducing the aging associated to the Li-BESS (reduced C_{rate}) but the required investment greatly overcomes the savings for delaying the reposition rate of the Li-BESS.

However, if the SCs are included in a previous stage of the dimensioning process of the HESS (Li-BESS and SCs), there are solutions where the savings justify the inclusion of the SCs, being the

optimal solution close to a configuration where the number of Li-BESS modules equals in energy the one required in the cycle. In the second analysis presented in this work, that corresponds to 10 Li-BESS modules, being the rest of the vessel consumption being covered by the SC stacks.

Future works, following the methodology presented in this paper, include modelling the DC/DC converter so switching and conduction losses can be considered. Besides, the SoH will be fed back in the Li-BESS model, so parameters and variables such as the SoC vary according to the maximum capacity of the Li-BESS. In this sense, the SoH limit for a Li-BESS replacement should be redefined, so it is replaced when there is no energy to deal with the cycle, not at 80%. At last, in future works the cost computation will include the capital recovery factor and annual discount rate, among other economic factors.

6. ACKNOWLEDGMENT

This work was developed under the financial support of the following Projects:

Project POSEIDON (ID: 101096457), which has received funding from European Union's Horizon Europe research and innovation program under HORIZON.2.5.7 - Clean, Safe and Accessible Transport and Mobility and HORIZON.2.5.6 - Industrial Competitiveness in Transport (HORIZON-CL5-2022-D5-01-02).

Project StoRIES (ID: 101036910), which has received funding from European Union's Horizon 2020 research and innovation program under H2020-EU.1.4. - EXCELLENT SCIENCE - Research Infrastructures (LC-GD-9-1-2020).

The authors would like to thank Balearia for providing vessel consumptions for the Li-BESS, as well as information about the Li-BESS equipped in the ferry ship.

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