

D1.2 Preliminary assessment of combined storage systems for the selected marine applications.

Document Identification			
Status	Final	Due Date	31/05/2024
Version	1.0	Submission Date	

Related WP	WP1	Document Reference	D1.2
Related Deliverables	D1.1/D3.1	Dissemination Level	Public
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Keywords
Electric vessel, ship, energy storage system, Li-ion battery, ultra-capacitor, SMES, power electronic converters

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Dissemination	Public	Version	1.0

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1. Abbreviations and acronyms

AHC	Active Heave Compensation
ADY	Active Days per Year
BESS	Battery Energy Storage System
BOL	Beginning of Life
DG	Diesel Generator
DoD	Depth of Discharge
DP / DP2	Dynamic Positioning / Dynamic Positioning Mode 2
EDL	End of design Life
EMS	Energy Management Strategy
EOL	End of Life
ESS	Energy storage system
ESR	Equivalent Series Resistance
FC	Fuel Cell
HE	High Energy
HESS	Hybrid Energy Storage System
HMPS	Hybrid Marine Power Systems
HP	High Power
KPI	Key Performance Indicators
LFP / G-LFP	Li-ion cell that uses Graphite as the anode and Lithium Iron Phosphate (LiFePO ₄) as the cathode
LTO-LMO	Li-ion cell that uses Lithium Titanium Oxide as the anode and a combination of Lithium Manganese dioxide (LMO) as the cathode
LTO-NMC	Li-ion cell that uses Lithium Titanium Oxide as the anode and a combination of Nickel, Manganese and Cobalt as the cathode
MCC / MCD	Maximum continuous charge/discharge
MPC / MPD	Maximum peak charge/discharge
NMC / G-NMC	Li-ion cell that uses Graphite as the anode and a combination of Nickel, Manganese and Cobalt as the cathode



NMC-E	Li-ion NMC cells/batteries designed focus on high energy density
NMC-P	Li-ion NMC cells/batteries designed focus on high power density
OCV	Open Circuit Voltage
OSV	Offshore Service Vessel
PS	Peak Shaving
PSV	Platform Supply Vessel
SC	Super Capacitor
SFC	Specific Fuel Consumption
SL	Strategic Loading
SMES	Superconducting magnetic energy storage
SOC	State of Charge
SOH	State of Health
SR	Spinning Reserve
TRL	Technology readiness level
TSHD	Trailing Suction Hopper Dredger
ZEWT	Zero-emission waterborne transport



2. Introduction

A single storage technology may not fit well the requirements in terms of energy capacity and rated power for a specific application. Thus, the dimensioning of the Energy Storage System (ESS) should be based on the most restrictive requirement. For example, the power requirements for a specific marine application can exceed the limits of a Battery Energy Storage System (BESS) sized based on energy capacity leading to the need to oversize the BESS for fulfilling the power requirements. Alternatively, high-power ESS technologies (like supercapacitors or SMES) can be considered instead of batteries to fulfill the power requirements. However, this may also need to be overrated for the constraints on the required energy capacity leading again to oversizing. A hybrid ESS (HESS) combining a storage technology with high energy density (HE-ESS) with another technology with high power density (HP-ESS) could be designed to better fit the load demand. This could result for some specific cases in a better combined solution by leveraging on the strengths of two ESS technologies and still provide sufficient energy and power to meet the demand of the vessel. Indeed, the HESS can be downsized compared with a BESS in the sense that the overall selected metric for evaluation (e.g. cost, volume, weight) including all the elements for the combined solution is lower than for a solution based only on a single storage technology.

The storage elements depending on their technology deteriorate and progressively lose capacity. Moreover, internal resistances tend to increase with aging, and this limits the maximum power that the unit can supply. The estimation of the fractional capacity degradation (capacity fades in a period with defined conditions) depends on whether the ESS is in operation (charging/discharging) or not. When the ESS is not in operation, the phenomenon is known as calendar degradation (aging during storage). On the other hand, if the ESS is in operation, then a cycling degradation will occur [1]. Thus, an additional requirement to be carefully assessed is related to lifetime and loss of capacity due to cycling and calendar aging. This effect is especially critical for electrochemical batteries that should be dimensioned based on their capacity in their worst degradation state. A hybrid topology can reduce high-current stress factors from the battery resulting in smaller temperature peaks in the battery cells and in a longer lifetime. The efficiency, reliability, and flexibility of the marine power system can also be increased with better utilization of the batteries.

This work presents a methodology for sizing an ESS for a vessel adopting a HESS whenever beneficial. The HESS assumes two storage technologies with fully controllable power flow via power electronic converter interfaces. The objective of the methodology presented is to identify the optimal sizing of the storage units and to assess if a HESS is indeed preferable.

2.1. Background and preliminary considerations

The possible advantages offered by a HESS are illustrated in FIGURE 2-1 on a plane reporting the power and energy ratings on the axes. Two storage technologies with very different performance in terms of power and energy density are considered. It can be reasonably assumed that the power and energy capabilities change linearly with the size of the storage system. This implies that each of the storage components will have the associated capabilities lying on a line indicated in the figure as a dashed line whose slope is highlighted visually by an arrow. The combination of power and energy requirements indicated by the red



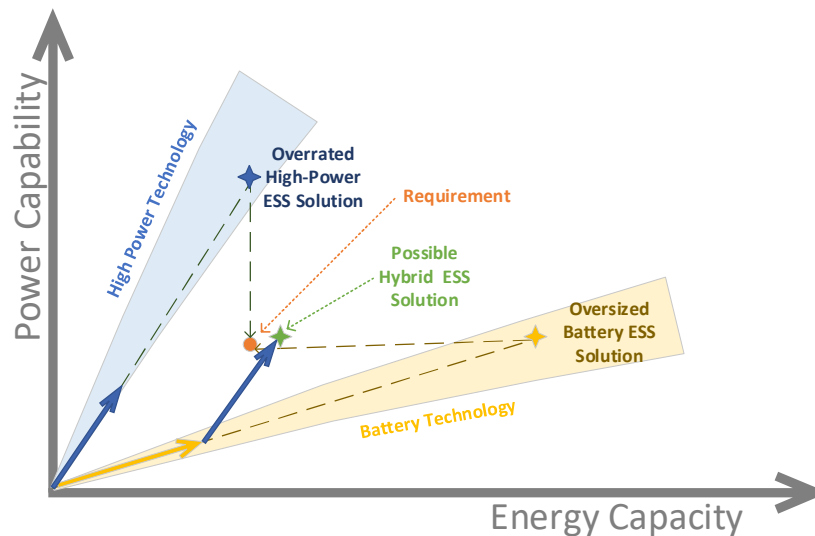


FIGURE 2-1 OVERSIZING AND/OR OVERRATING OF ESS TECHNOLOGIES TO MEET POWER AND ENERGY REQUIREMENTS.

dot clearly does not match neither of the two storage technologies. The storage with the least power density will have to be sized based on the power requirements resulting in an oversizing of the storage capacity. By contrast, the other storage component will have to be sized according to the energy capacity requirements resulting in an oversizing of the power capability. The sizing requirements and the oversizing needs are shown in the figure. A combined system can offer performance with an intermediates slope depending on the grade of hybridization. This is shown in the figure combining the arrows and reaching a point that fulfils both the energy and the power requirements with a hybrid storage system.

Presently, several technologies approved for installation on board of vessels are available for storage of electrical energy. Main discriminating factors are the power density and the energy density because these are directly related to capabilities to cover base loads for long intervals of time or short power fluctuations. Li-ion batteries are the most popular technology for marine applications. The main characteristics and performance of five battery modules based on different Li-ion chemistries/technologies available for marine applications are presented in the TABLE 1 and briefly summarized below:

- **G-NMC:** Li-ion cell that uses Graphite as the anode and a combination of Nickel, Manganese and Cobalt as the cathode. Li-ion cells based on a given chemistry can be designed to deliver high power, or high energy, so they are known as power cells and energy cells. There are two types of G-NMC technologies in TABLE 1, based on either energy or power cells.
- **G-LFP:** Li-ion cell that uses Graphite as the anode and Lithium Iron Phosphate (LiFePO_4) as the cathode.
- **LTO-NMC:** Li-ion cell that uses Lithium Titanium Oxide as the anode and a combination of Nickel, Manganese and Cobalt as the cathode.
- **LTO-LMO:** Li-ion cell that uses Lithium Titanium Oxide as the anode and a combination of Lithium Manganese dioxide as the cathode.

On the other hand, TABLE 2 presents the reference performance for the Ultra High-Power ESS technologies considered in this work.



TABLE 1 PERFORMANCE EXAMPLE OF LI-ION BATTERY ESS MODULES AVAILABLE FOR MARINE APPLICATIONS.

Technology	G-NMC/ Energy	G-NMC/ Power	G-LFP	LTO-LMO	LTO-NMC
Reference Module	XMOD 123E	Orca Energy	Seenergy 48P Module	24V-70Ah Gen 4.3	HP-7
Manufacturer	XALT Energy	Corvus Energy	Saft	Altairnano	E-mobitech
Capacity [Ah]	138	120	60	68	10
Nominal Energy [kWh]	12,3	5,65	2,7	1,5	6,9
Voltage nominal [V]	88,6	47,2	46,2	22	691
Discharge Current rate [C-rate] (cont./peak)	1 / 2	3 / 5	4 / 6	7,4/ 13,3	20 / 36
Charge Current rate [C-rate] (cont./peak)	0,4 / 0,5	3 / 5	4 / 6	7,4/ 13,3	20 / 36
Specific Energy [Wh/kg]	160	94	70	53	26
Energy Density [Wh/dm ³]	220	140	77	112	34
Specific Power [W/kg] (peak, 50%SoC)	320	388	420	700	936
Power Density [W/dm ³] (peak, 50%SoC)	440	453	462	1478	1224
Calendar Life, 30°C @EOL (80%SOH)	18 years*	18 years*	20 years	25 years	25 years*
Cycle life to 80%SOH.	4000 cycles @80%DoD, 0,3C/ 0,3C, 25°C	10000 cycles** @80%DoD, 1,2C/1,2C, 30°C	6000 cycles @80%DoD, 0,8C/0,8C, 25°C	25.000 cycles @100%DoD, 2C/2C, 25°C	60.000 cycles** @60%DoD, 5C/5C, 45°C

*Assumed based on average calendar life of similar cell chemistries.

**Based on approx. performance of NMC power cell P41 from LG Chem

***Based on Cycle life for 10Ah LTO cell from Toshiba

TABLE 2 REFERENCE PERFORMANCE EXAMPLE FOR ULTRA HIGH-POWER ESS TECHNOLOGIES.

Technology	Super Capacitor	SMES
Reference Module	SkelMod162V62F	741 kJ, 200kW-2.5s
Manufacturer	Skeleton	ASG Superconductors
Capacity [Ah]	1.86	0.275
Nominal Energy [kWh]	0.226	0.206
Voltage nominal [V]	121,5	750
Charge/Discharge Current rate [C-rate]	124 @ cont. 1495 @ peak	121 @28s /970 @2.5s 1670 @peak
Usable Energy [%]	75 % @50% Rated Voltage	67.5% @200kW 99.5% @25kW
Specific Energy [Wh/kg]	6,8	0.206
Energy Density [Wh/dm ³]	4,9	0.666
Specific Power [W/kg] (peak, 50%SoC)	10166	345
Power Density [W/dm ³] (peak, 50%SoC)	7325	5515
Calendar Life, 30°C @EOL (80%SOH)	25 years	Negligible
Cycle life to 80%SOH.	1.000.000 @75% DoD, 15C/15C, 35°C	Negligible

3. ESS Sizing Methodology and Evaluation Methods

3.1. HESS Evaluation Framework

FIGURE 3-1 shows the HESS evaluation framework implemented to provide a preliminary assessment of lifetime, cost and/or emission savings with utilization of combined storage solutions for the selected case studies. The main inputs for the HESS framework are the vessel mission profile, the general ESS requirements, and the ESS technology performance parameters. The vessel mission profile and the general ESS requirements are part of the case study definition. The selection of the battery technology and HP-ESS technology for a given vessel type can be considered as an additional degree of freedom.

For the case of zero emissions (full electric) vessels, the HESS should provide the full load power defined by the vessel mission profile. The HESS power profile can be then calculated from the vessel power profile together with the information about charging availability. On the other hand, for the case of Hybrid Marine Power Systems (HMPS), the energy management strategy (EMS) for the vessel is necessary for defining the HESS power profile. The ship-EMS and the ESS functionalities bring additional degrees of freedom to the sizing algorithm, which allows to map the different trade-off between potential fuel savings and ESS requirements [1, 2].

Once the HESS power profile is defined, the EMS for HESS will determine how the power is split between the BESS and the HP-ESS. Thus, the power, energy, and cycling requirements given by the HESS power profile are translated into requirements for the BESS and the HP-ESS [3]. Here, an additional degree of freedom is added to the algorithm as different power split alternatives will result in different ESS subsystem requirements and therefore different combinations of installed capacity for BESS and HP-ESS. After the requirements in terms of power, usable energy, and cycling are established for the BESS and the HP-ESS, the sizing can be performed and the actual required energy capacity to be installed is calculated. Finally, the additional components of each subsystem, like the power converters and/or cooling systems are considered to give an estimation of the performance of each HESS solution.

The approach in FIGURE 3-1 is focusing on combining Li-ion battery technologies with ultra-high-power ESS technologies listed in TABLE 2, but it can be extended to adopt different kind of high-energy dense ESS in combination with high-power ESS. The proposed methodology maps the HESS design space, defined by the possible combinations of power allocation between BESS and HP-ESS, to a HESS global performance space framed by the required capacity of each ESS (associated to the power allocation combination) to fulfil the vessel mission profile. The performance space can include several metrics as the total capital cost, volume, weight, expected HESS lifetime, installed capacity and power capability.

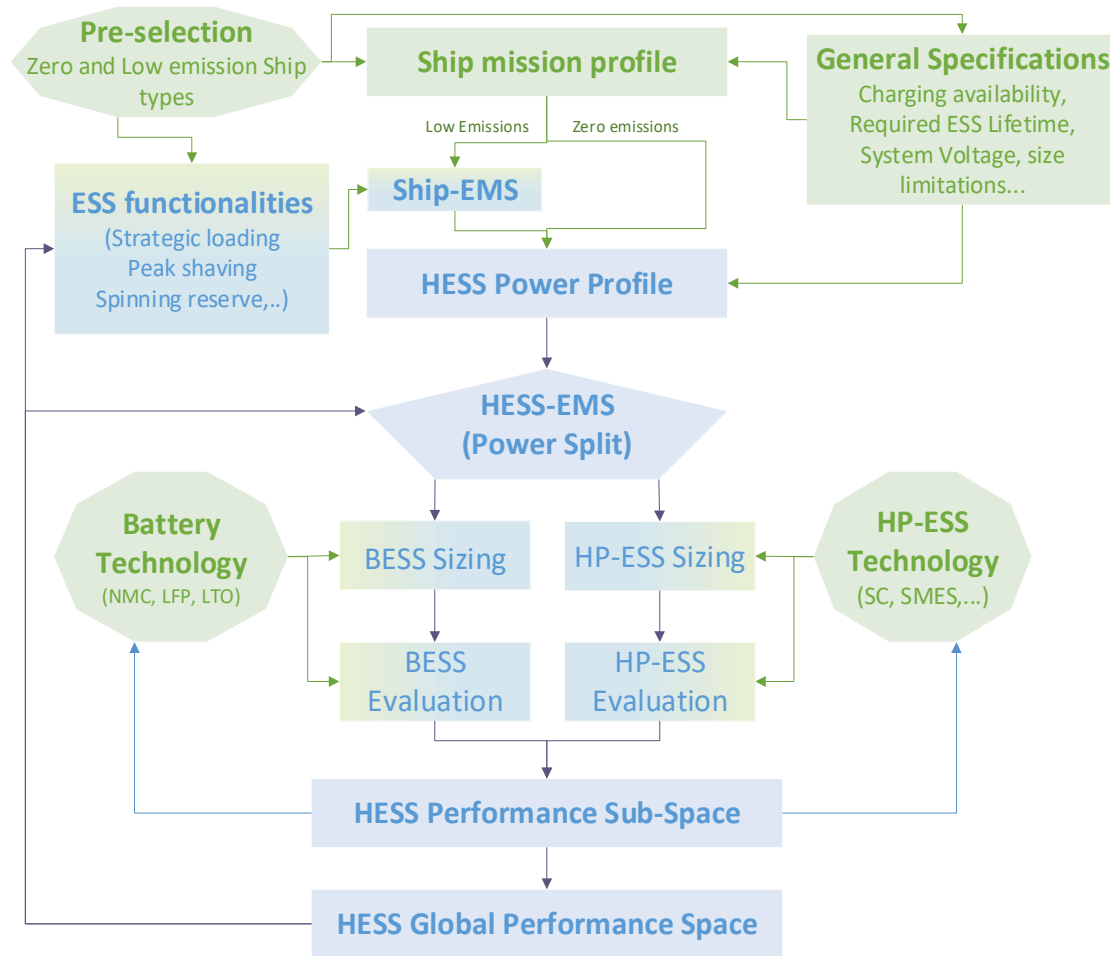


FIGURE 3-1 HESS EVALUATION FRAMEWORK.

The main inputs for the algorithm are as follows:

- **Vessel Mission Power profile:** Definition of the power time series to be supplied by the ESS and its number of yearly operational cycles. It is the vessel load power time series that needs to be supplied by the ESS at end-of-design-life. It could be estimated from preliminary vessel profile data, which can be obtained from available log data, simulations or data reported in the literature.
- **Required ESS lifetime:** It is the minimum lifetime to be met by the ESSs, and the ESS needs to be sized accordingly.
- **BESS and HP-ESS reference technology parameters:** Definition of the required ESS technology parameters for sizing algorithm and evaluation of the ESSs. ESS parameters for sizing algorithm are related to degradation and power capability performance, while ESS evaluation parameters depend on the target objective function which may include physical dimensions, cost, and losses.
- **HESS design space granularity and limits:** It defines the range and the number of design alternatives to be evaluated/mapped to the HESS performance space.

The methodology is composed of mainly five processes, which are summarized as follows:

1. **HESS design space definition:** The vessel mission power profile is analysed to establish an appropriate range for the parameters of the HESS energy management strategy (EMS), as well as the number of discrete values to be evaluated within the defined parameter range. Each combination of HESS-EMS parameters will result in different power allocations rules between BESS and HP-ESS obtaining different power time series for each ESS which are translated into different ESS design requirements.
2. **HESS Energy Management Strategy (EMS):** Algorithm to split the required power for the HESS into two power output profiles for the BESS and the HP-ESS.
3. **BESS and HP-ESS Sizing:** This process estimates the required energy to be installed for the ESS to fulfil the minimum requirements accounting for ESS technology performance and design lifetime.
4. **HESS Evaluation and performance space:** The evaluation process involves the modelling of accounted performance indices to map the HESS design space into the HESS performance space. Example of performance indices are the total installed capacity, the HESS cost, the physical size (volume and/or weight), the power or/and energy efficiency, or a combination of some/all the previous. This work focus on potential gains in required installed energy of HESS versus only BESS, as the HESS physical size and cost are proportional to the required installed capacity.
5. **HESS Pareto Optimality Sizing:** After the HESS performance space is mapped, then the pareto optimality between required installed energy for BESS and HP-ESS is obtained.

3.2. Performance indices and reference technologies

TABLE 3 shows the reference ESS technology parameters used in this work. Additional assumptions and design prerequisites are listed below:

- 10% safety margin in the ESS peak current has been considered in all cases.
- Ship lifetime 30 years
- For BESS and SC 10 years design life is assumed.
- For SMES a lifetime equal to ship lifetime is assumed.
- ESS end of life (EOL) criteria = ESS retaining less than 80% of the initial capacity.

A set of performance indices for the full electric vessel has been considered for the optimization:

- HESS installed energy capacity is defined as the sum of the BESS energy capacity and the HP-ESS energy capacity.
- HESS Cost: Sum of BESS cost and HP-ESS cost. The cost of the BESS/HP-ESS is calculated multiplying the energy capacity by the reference cost per kWh listed in **TABLE 3**
- HESS Volume: Sum of BESS volume and HP-ESS volume. The volume of the BESS/HP-ESS is calculated multiplying the energy capacity by the reference energy density listed in **TABLE 3**.



TABLE 3 REFERENCE ESS TECHNOLOGY PARAMETERS

Technology		G-NMC-E	G-NMC-P	G-LFP	LTO-LMO	LTO-NMC	Super Capacitor	SMES
Discharge Current rate [C-rate] (cont./peak)		1 / 2	3 / 5	4 / 6	7,4/ 13,3	20 / 36	124 / 1495	970 / 1670
Charge Current rate [C-rate] (cont./peak)		0,4 / 0,5	3 / 5	4 / 6	7,4/ 13,3	20 / 36	124 / 1495	970 / 1670
Specific Energy [Wh/kg]		160	78,5	70	53	26	6,8	0.206
Energy Density [Wh/dm ³]		220	90.3	77	112	34	4,9	0.666
Usable energy (SOC range) [%]		80	80	80	90	90	75	67.5 ^e
ESS Cost [EUR/kWh]		400 ^c	700 ^c	350 ^c	1100	1400 ^c	5000 ^d	144000 ^d
Calendar degradation [%/year]		1,11 ^a	1,11 ^a	1	0,8	0,8 ^a	0,8	NA
Cycle Life ^c	Cycles to 80%SOH.	4.000	10.000	6.000	25.000	60.000 ^b	1.000.000	NA
	Reference DoD [%]	80	80	80	100	60 ^b	75	NA
	Ref. Charge/discharge rates	0,3/0,3	1,2/1,2	0,2/0,2	2/2	5/5 ^b	15/15	NA
	Ref. temperature [°C]	25	30	25	25	45 ^b	35	NA
	DoD stress factor, β	1.6844	2.2093	2.1327	2.1314	1.7113	2.8644	NA
	Charge rate stress factor, α_c	1.6185	1.1162	0.7439	-0.58012	-0.58012	-1	NA
	Discharge rate stress factor, α_D	0.9180	0.5584	1.3382	-0.58012	-0.58012	-1	NA
Temperature stress factor, γ		3664	8266	3684	4650	6495	6976	NA

^a Assumed based on average calendar life of similar cell chemistries.

^b Based on Cycle life for 10Ah LTO cell from Toshiba

^c Assumed based on similar cell performance and literature [21, 22]

^d Specified by manufacturer (Skeleton for SC and ASG Superconductor for SMES)

^e Possible to increase for reduced cont. current rates (up to 99.7% for 121 C-rate).

- **HESS Weight:** Sum of the BESS weight and HP-ESS weight. The weight of the BESS/HP-ESS is calculated by multiplying the energy capacity by the reference specific energy listed in [TABLE 3](#)
- **OF_{CVW}:** Objective function combining normalized HESS cost, volume, and weight, taking as reference the BESS-only solution.

$$OF_{CVW} = \frac{Cost_{HESS}}{Cost_{BESS}} + \frac{Volume_{HESS}}{Volume_{BESS}} + \frac{Weight_{HESS}}{Weight_{BESS}}$$

Additional performance indices should be added for the case of hybrid marine power systems:

- Fuel consumption → Fuel savings/reduction compared with a reference case.
- Economic Benefit: Taken as the difference between the total fuel savings for the ESS design lifetime and the ESS cost.
- Number of Starts and Stops for the generators.

3.3. Energy Management Strategies for Hybrid Marine Systems

The ESS/HES sizing methodology proposed in this work can be applied to both full electric and hybrid marine power systems. In the case of full electric vessel, the ESS should supply all the vessel load. In the case of a low emission vessel, the HMPS consisting of Diesel/Gas Generators (DGs) and ESS supplies the vessel loads, so the energy management strategy should decide how to share the load between DGs and ESS. The HMPS performance depends on the selected/designed Energy Management Strategy (EMS) for a given operating mode of the marine vessel. Different operating modes (e.g. dynamic positioning, roll-on/roll-off operation, or offshore petroleum discharge) can be considered by associating them to a load profile and operating constraints. The total performance can be estimated by weighted average considering the relative time that the vessel is at each operation mode. A multi-objective design approach is adopted and the performance indices of the HMPS are compared against a reference case, a marine power system with similar architecture but without ESS.

The main HMPS performance metric considered to the use of ESS is the fuel consumption reduction. The analytical method reported in [2, 1] for estimation of fuel savings potential resulting from installation of ESS in marine vessels is considered in this work. To estimate the fuel consumption, the methodology basically requires two inputs, the Specific Fuel Consumption (SFC) of the DGs and the load profile. To find the reference operating rule with no ESS present and no redundancy required, the following optimization problem is solved to find the optimal number of DGs to reduce fuel consumption:

$$SFC_{DG}(P_L) = \min_{n_{DG}}[SFC_{DG}(n_{DG}, P_L)]$$

$$\text{subject to } n_{DG} \cdot (1 - p_{RM}) \cdot P_{DG.mx} \geq P_L$$

where n_{DG} is the number of running DGs, P_L is the load power, $P_{DG.mx}$ is the DG rated power and p_{RM} is the DGs reserve margin. A DGs reserve margin p_{RM} means that a new generator should be turned-on if the actual load of running generators reaches $1 - p_{RM}$ of the maximum available DGs power capacity.

When the HMPS is required to operate with redundancy, the system must continue to supply the given load in case one of the running DGs fails, so the following optimization problem is solved to find the optimal operating rule:

$$SFC_{DG,SR}(P_L) = \min_{n_{DG}}[SFC_{DG}(n_{DG}, P_L)]$$

$$\text{subject to } (n_{DG} - 1) \cdot (1 - p_{RM}) \cdot P_{DG.mx} \geq P_L$$

The ESS profile will depend on the intended ESS functionality within the power marine system. Three main functionalities have been considered in this work:

- **ESS as Spinning Reserve:** This functionality is very relevant for marine vessels including dynamic position mode 2 (DP2). Indeed, without an ESS this would requires a redundancy for the electric generators, forcing to have at least two generators running at reduced loading during DP operation which is not fuel efficient. The ESS can be used as backup source in case of contingencies, so the HMPS can be operated with the optimal number of running DGs while still fulfilling the redundancy requirements.



- **ESS for Peak Shaving:** In marine offshore operations (especially in rough sea conditions), loads are often intermittent and characterized by several high peaks of power which stress the generators accelerating their wear. Moreover, these rapid increases in load can cause genset protections to trip and cascade blackouts on the ship. Energy storage can be used for power support requiring a charge/discharge cycle of 1-20 s with many cycles per day.
- **ESS for Strategic Loading:** EMS for Strategic Loading uses the ESS to minimize fuel consumption by shifting the operation point of DGs.

3.4. Energy Managements Strategy for Hybrid Energy Storage

In a full electric vessel, the HESS power profile is identical to the ship mission profile since no other energy sources are available. In general, the power profile as a base for the HESS sizing should cover the full lifetime of the vessel. However, it is reasonable to assume that this can be decomposed in a sequence of N_{ts} power time series of shorter length (e.g. a day) that are repeated. Each of this series can be representative of a specific operating scenario reflecting eventually seasonal variations, or differences in scheduled times and type of operation. For each time series it should be specified the expected number of repetitions in a year or eventually in the lifetime of the vessel.

The operation of a HESS requires the definition of an energy management strategy for sharing the power between the High-Energy (HE) -ESS (i.e. the BESS) and the High-Power (HP) -ESS subsystems. This represents a degree of freedom and should reflect a design objective. If losses in the power electric converters are neglected, the power in the HESS can be expressed as:

$$P_{HESS}(t) = P_{HE}(t) + P_{HP}(t)$$

where, $P_{HESS}(t)$ is the HESS power time series, $P_{HE}(t)$ is the power time series split to HE-ESS sub-system and $P_{HP}(t)$ is the power time series split to HP-ESS sub-system.

This work assumes an allocation of the power based on a first order low pass filter acting on the load power demand. Indeed, the output of the low pass filter containing the base load can be assigned to the HE-ESS while the remaining power can be assigned to HP-ESS. An advantage of this choice is that it can be easily implemented in a real power management system. The low pass filter can be parametrized to customize and adapt the performance. The energy management implementation is shown in FIGURE 3-2, which is the content of the block called HE-HP power split in the power split algorithm shown in FIGURE 3-3. The process is repeated for all the time series composing the power profile.

The implementation of the low pass filtering requires three parameters to be defined: the low pass filter cut-off frequency (F_0), the maximum discharge power of HE battery ($P_{HE.DCHmx}$) and the maximum charge power of HE battery ($P_{HE.CHmx}$). This parametrization leads to a large variability in the behaviour and flexibility. However, only two of these parameters (F_0 and $P_{HE.DCHmx}$) have been considered as free design parameters to guarantee the energy balance of the resulting power time series. The parameter $P_{HE.CHmx}$ has been set as the maximum charge power of the time series and then recalculated based on the energy used and available charging time. Different combinations of F_0 and $P_{HE.DCHmx}$ are explored in the

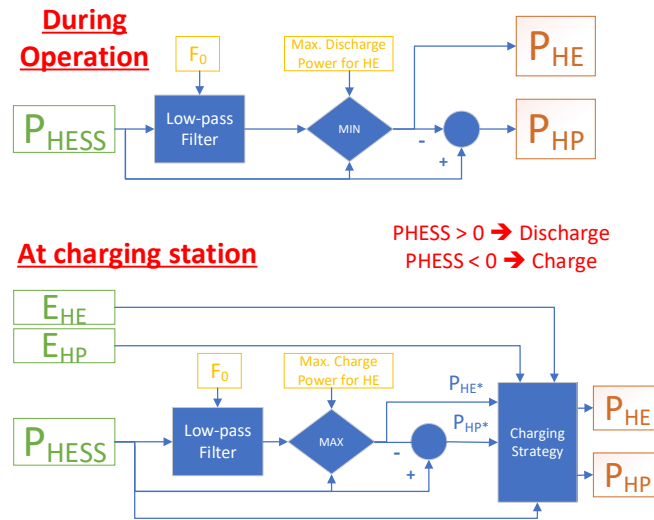


FIGURE 3-2 ENERGY MANAGEMENT STRATEGY BASED ON LOW PASS FILTERING FOR ZERO-EMISSION VESSELS. (TOP: STRATEGY DURING HESS DISCHARGING; BOTTOM: STRATEGY DURING HESS CHARGE OPERATION AT CHARGING STATION).

optimization, implying also that the filter parameters used for one of the time series within the given power profile can be different from the filter parameters used for the other time series of the given power profile. This implies that for each application power profile (composed by N_{ts} power time series) the power split design space has $2 \times N_{ts}$ free design parameters (two filter parameters per each time series).

Additionally, three charging strategies are considered:

1. Prioritizing HE-battery charge:

- During the HESS discharge state, the battery discharge power follows the low pass filter output.
- During the HESS charge state, the battery charge power follows the low pass filter, but battery charge is prioritized and the SC/SMES is fully charged only after the battery is fully charged.
- The implementation considers an additional constraint on the directions of the power flows to avoid power exchange between the ESS sub-systems:

$$\begin{cases} P_{HE}(t) \geq 0 \ \& \ P_{HP}(t) \geq 0 \quad \forall \ P_{HESS}(t) \geq 0 \\ P_{HE}(t) \leq 0 \ \& \ P_{HP}(t) \leq 0 \quad \forall \ P_{HESS}(t) < 0 \end{cases}$$

2. Forcing/Prioritizing HP-ESS (SC/SMES) to fully charge during HESS discharging state:

- During the HESS discharge state, the battery discharge power is not fully following the low pass filter output but is modified to force the HP-ESS to be charged right after using it in the peaks (maximum) periods of HESS discharge power. This may result in higher average power per cycle for the battery but reduces the size of the HP-ESS.
- During the HESS charge state, if needed, the HP-ESS is charged first then HE-battery is charged after.

3. Prioritizing HP-ESS (SC/SMES) charge during HESS charge state:

- During the HESS discharge state, the battery discharge power follows the low pass filter output.
- During HESS charge state, the low pass filter output is modified to prioritize charging of HP-ESS

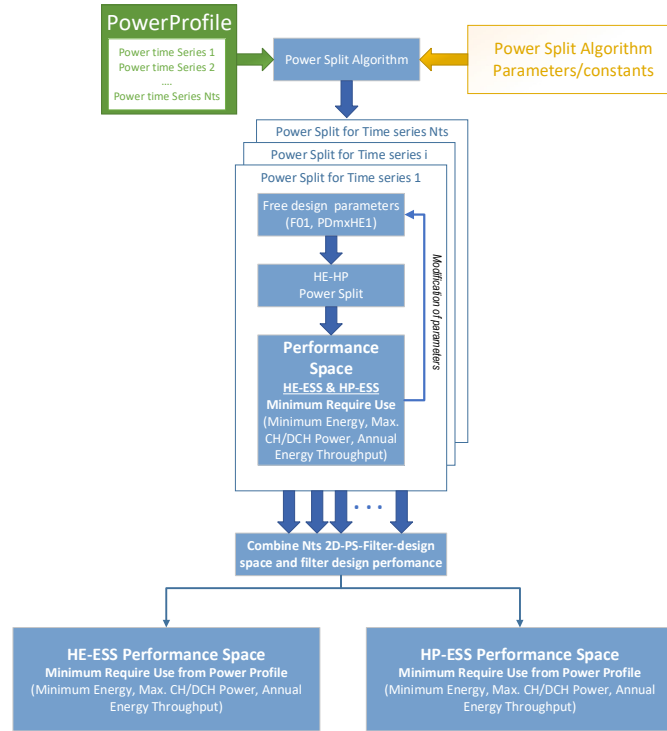


FIGURE 3-3 POWER SPLIT ALGORITHM

while also charging the battery.

Two requirement subspaces are obtained in this step, associated to each ESS sub-system. Each requirement subspace is defined by five specific requirements, calculated from the power time series allocation to each ESS sub-system:

- **The minimum usable energy of the ESS sub-system (E_{MRU}):** it is the minimum energy capacity that needs to remain at the end of design life. It is possible to estimate the required energy for each power time series associated to a battery sub-system by the difference between maximum and minimum change in stored energy, which is calculated by the integration of the power time series. The required energy (E_{reqHE}) by a power time series $P_{HE}(t)$ split to the HE battery can be estimated by:

$$E_{reqHE} = \max \left(\int P_{HE}(t) \cdot dt \right) - \min \left(\int P_{HE}(t) \cdot dt \right)$$

Then, the minimum required usable energy (E_{MRU}) of the battery sub-system is equal to the maximum required energy from all N_{ts} power time series of the power profile:

$$E_{MRU} = \max(E_{req1}, E_{req2}, \dots, E_{reqNts})$$

- **The required maximum continuous and peak charge power (P_{MCC} & P_{MPC}):** It is possible to estimate a minimum required charge power associated to each power time series by taking the maximum between the required energy per cycle and the available charging time per cycle (assuming energy balance per cycle). Then, the required maximum continuous charge power is calculated as the

maximum value along all the required charge power associated to the N_{ts} power time series of the power profile.

- **The required maximum continuous and peak discharge power (P_{MCD} & P_{MPD}):** This is estimated from the maximum value of all maximum discharge power associated to all N_{ts} power time series of the power profile.
- **The annual energy throughput (AET):** The energy throughput associated to each power time series can be found by integrating either charge power or discharge power, or simply approximated by integrating the unsigned power and divide by 2; e.g., the annual energy throughput ($AET_{HE,i}$) associated to the power time series $P_{HE,i}(t)$ split to the HE battery can be estimated by:

$$AET_{HE,i} = \int_{t=0}^{t=1ye} \frac{|P_{HE,i}(t)|}{2} \cdot dt$$

Then, the annual energy throughput associated to a given power profile is calculated by adding the energy throughput associated to each power time series composing the power profile, e.g. for the HE battery sub-system:

$$AET_{HE} = \sum_{i=1}^{N_{ts}} AET_{HE,i}$$

- **Equivalent energy cycles:** The rain-flow algorithm has been used to estimate the equivalent energy cycles and cycling characteristics associated to power time series $P_{HE}(t)$ and $P_{HP}(t)$. The rain-flow build-in MATLAB function has been used, which computes cycle counts for fatigue analysis of the load time history according to the ASTM E 1049 standard.

FIGURE 3-4 shows examples of the power time series obtained by the energy management algorithm when using different parameters. The cycled energy associated with the resulting power time series are also plot.

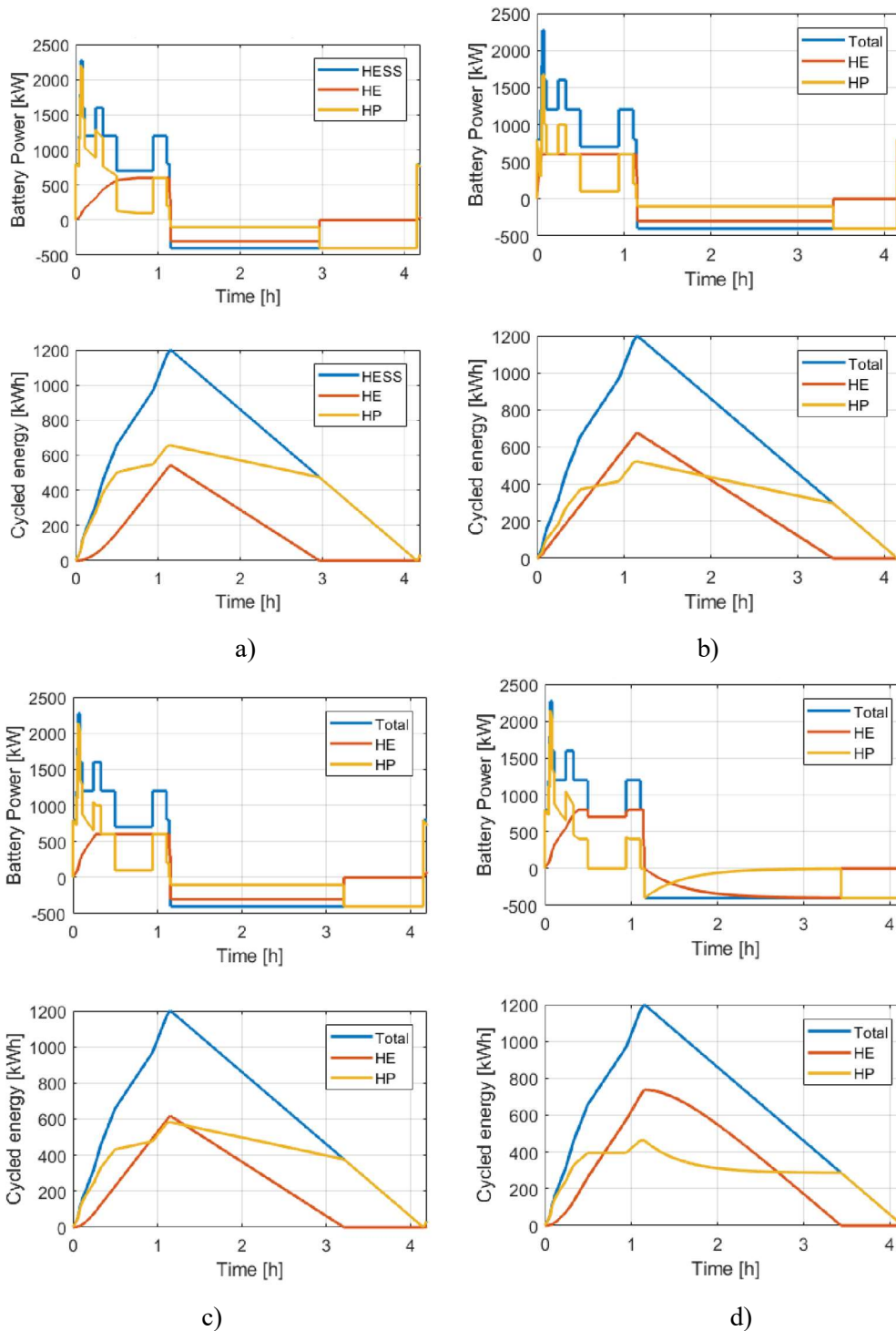


FIGURE 3-4 EXAMPLE OF TIME SERIES OBTAINED BY THE POWER SPLIT ALGORITHM WITH A) $F_0=50\text{MHZ}$, $P_{HE.DCHmx} = 600\text{kW}$, $P_{HE.CHmx} = 300\text{kW}$; B) $F_0= 1000\text{MHZ}$, $P_{HE.DCHmx} = 600\text{kW}$, $P_{HE.CHmx} = 300\text{kW}$; C) $F_0= 100\text{MHZ}$, $P_{HE.DCHmx} = 600\text{kW}$, $P_{HE.CHmx} = 300\text{kW}$; AND D) $F_0= 100\text{MHZ}$, $P_{HE.DCHmx} = 800\text{kW}$, $P_{HE.CHmx} = 400\text{kW}$;

3.5. Energy Storage Sizing Methodology

There are different factors to be considered to ensure enough remain battery capacity at the end of design life (E_{EDL}). The ESS sizing algorithm estimates the minimum capacity to be installed considering the following criteria:

- to charge and discharge the **minimum usable energy** prescribed by the load profile to the end of design life (EDL) and maintaining the State of Charge within the defined minimum (SOC_{mn}) and maximum (SOC_{mx}) set design limits (e.g. between 10% and 90%):

$$E_{EDL} \geq \frac{E_{MRU}}{SOC_{mx} - SOC_{mn}}$$

- to allow charging/discharging power at least as large as the **required maximum continuous** (P_{MCC}/P_{MCD}) and **peak** (P_{MPC}/P_{MPD}) **charging/discharging power** in the defined load profile at the EDL. The equivalent circuit including the ESS Open Circuit Voltage (OCV) and ESS equivalent series resistance (ESR) can be used to approximate the correlation between ESS current (I_{ESS}) and power (P_{ESS}), as follows:

$$P_{ESS} = I_{ESS} \cdot (OCV - ESR \cdot I_{ESS})$$

Rearranging to express in term of current rates ($C_{rate} = I_{ESS}/Ah_{ESS}$) and nominal energy at BOL ($E_{BOL} = V_N \cdot Ah_{ESS}$):

$$\frac{P_{ESS}}{E_{BOL}} = C_{rate} \cdot \left(\frac{OCV}{V_N} - \frac{ESR \cdot Ah_{ESS} \cdot C_{rate}}{V_N} \right)$$

Neglecting the OCV and ESR dependencies with SOC and assuming that the ESS is built up by connecting n_s reference modules/cells in series to achieve the required voltage (V_N) and n_p parallel connected strings to achieve the required capacity (Ah_{ESS}):

$$\frac{P_{ESS}}{E_{BOL}} = C_{rate} \cdot (1 - k_{\Delta REF} \cdot C_{rate})$$

$$k_{\Delta RE} = \frac{k_{R,EOL} \cdot ESR_{REF} \cdot Ah_{REF}}{V_{N,REF}}$$

where ESR_{REF} is the ESR of the reference module/cell with nominal voltage and capacity, $V_{N,REF}$ and Ah_{REF} , respectively, and $k_{R,EOL}$ is the expected increment of ESR at EOL (typically $k_{R,EOL} = 2$). Finally, accounting for the required maximum continuous (P_{MCC}/P_{MCD}) and peak (P_{MPC}/P_{MPD}) charging/discharging power, the following conditions should be satisfied:

$$E_{BOL} \geq \frac{P_{MCC}}{C_{rate,MCC} \cdot (1 - k_{\Delta REF} \cdot C_{rate,MCC})} \quad \& \quad E_{BOL} \geq \frac{P_{MPC}}{C_{rate,MPC} \cdot (1 - k_{\Delta REF} \cdot C_{rate,MPC})}$$

$$E_{BOL} \geq \frac{P_{MCD}}{C_{rate,MCD} \cdot (1 - k_{\Delta REF} \cdot C_{rate,MCD})} \quad \& \quad E_{BOL} \geq \frac{P_{MPD}}{C_{rate,MPD} \cdot (1 - k_{\Delta REF} \cdot C_{rate,MPD})}$$

where $C_{rate,MCC}$, $C_{rate,MCD}$ are the maximum continuous charge and discharge rates for the reference module, respectively, and $C_{rate,MPC}$, $C_{rate,MPD}$ are the maximum peak charge and discharge rates for reference module, respectively.

- to allow the energy cycling prescribed by the input load profile without causing battery cells to reach their end of life before end of design life:

$$Q_{Cal} + Q_{Cycle} \leq Q_{lossEOL}$$

- to ensure that the calendar capacity degradation alone will not reduce the storage capacity, before end of design life to such an extent that State of Charge goes outside the set design limits for the defined load profile:

$$E_{BOL} - E_{EDL} \leq Q_{cal}(N_{DL})$$

- to ensure that the cycling capacity degradation, in combination with the calendar capacity degradation in non-used periods, will not reduce the remaining capacity at end of life to such an extent that the State of Charge goes outside the set design limits for the defined load profile:

$$E_{BOL} - E_{EDL} \leq Q_{cal} + Q_{cycle}$$

Each of the previously mentioned criteria gives a minimum required capacity to be installed (E_{BOL}), so this implies that the minimum capacity to install is given by the maximum among all calculated energy capacities.

The aging process in battery cells is reflected mainly in capacity loss and increment of internal resistance. In this work, it has been considered the capacity degradation as the main end of life criterion. Thus, the EOL criterion ($k_{EOL} = 20\%$) for the ESS has been related to the capacity fade of battery cells [1]:

$$k_{EOL} = \left(1 - \frac{E_{EOL}}{E_{BOL}}\right) \cdot 100\%$$

$$k_{R.EOL} = \frac{ESR_{EOL}}{ESR_{BOL}}$$

where E_{BOL} is the ESS total energy capacity at beginning of life (BOL) and E_{EOL} is the remaining ESS capacity at end of life. The following assumptions have been accounted:

- As the end-of-life criteria has been linked to the capacity fade, then the degradation model only considers the effects on capacity fade given by calendar aging and cycling degradation. However, overall increment on ESR is considered to fulfil power requirements at EOL.
- The calendar aging is assumed as a linear process, reducing the capacity with an amount equal to a fixed percentage of the initial capacity whenever the battery is not in use. A battery with 1% calendar aging per year will then have 90% of its initial capacity after 10 years and 80% after 20 years.
- Calendar aging is assumed to apply whenever the battery is not cycled, that is, when the load profile has periods of zero power flow. It is assumed that cycle degradation also includes the calendar degradation.
- It is assumed that superposition applies such that the incremental effect of each cycle can be added, and such that incremental calendar capacity loss can be added to the capacity loss due to the cycles. This means that it is assumed that the capacity loss is the same independently of the sequence of cycles and periods with no use of battery (calendar aging).

Based on the previous assumptions, the total degradation (ΔQ_{EDL}) at the end of design life (EDL) is estimated by:

$$\frac{Q_{lossEDL}}{E_{BOL}} = \Delta Q_{EDL} = \Delta Q_{cal} + \Delta Q_{cycle}$$

where ΔQ_{cal} is the total calendar degradation and ΔQ_{cycle} is the total cycling degradation at the EDL. The calendar degradation can be estimated by:

$$\Delta Q_{cal} = \frac{Q_{LossCal}}{100} \cdot \frac{(365 - ADY)}{365} \cdot T_{EDL}$$

where $Q_{LossCal}$ is the capacity loss per year due to calendar aging (in percent of initial capacity), ADY is the expected operating days per year, and T_{EDL} is the design lifetime in years.

On the other hand, the capacity loss associated to cycling degradation is estimated following the methodology described in [1].

$$\Delta Q_{cycle} = \frac{T_{EDL}}{T_{FOP}} \sum_{k=1}^{N_{cycle}} D_{Q.cyc(k)}$$

where BESS has been cycled N_{cycle} times at different conditions during the fundamental operating period T_{FOP} . The cycle life model based on fatigue theory reported in [4] in combination with the multi-factor cycle life prediction methodology reported in [5] have been used for estimation of the fractional cycling degradation per cycle ($D_{Q.cyc}$). The main assumptions are that the impact of the operational factors on the battery cycle life are approximated to be independent from each-other, as well as that the cycling degradation is uniformly distributed along the lifetime according to:

$$D_{Q.cyc} = \frac{0.01 \cdot k_{EOL.ref}}{N_{CL.ref}} \cdot \left(\frac{DoD}{DoD_{ref}} \right)^{\beta} \cdot \left(\frac{I_c}{I_{c.ref}} \right)^{\alpha_c} \cdot \left(\frac{I_D}{I_{D.ref}} \right)^{\alpha_D} \cdot e^{\gamma \cdot \left(\frac{1}{T_{c.ref}} - \frac{1}{T_c} \right)}$$

where DoD is the depth of discharge, T_c is the average battery/supercapacitor cell/module temperature, I_c and I_D are the charging and discharging currents/rates, respectively, β , α_c , α_D , and γ are the degradation stress factor fitting parameters for DoD, I_c , I_D and T_c , respectively, and $N_{CL.ref}$ is the number of cycles under reference conditions (DoD_{ref} , $I_{c.ref}$, $I_{D.ref}$, and $T_{c.ref}$) until the battery reaches its reference EOL criteria ($k_{EOL.ref}$).

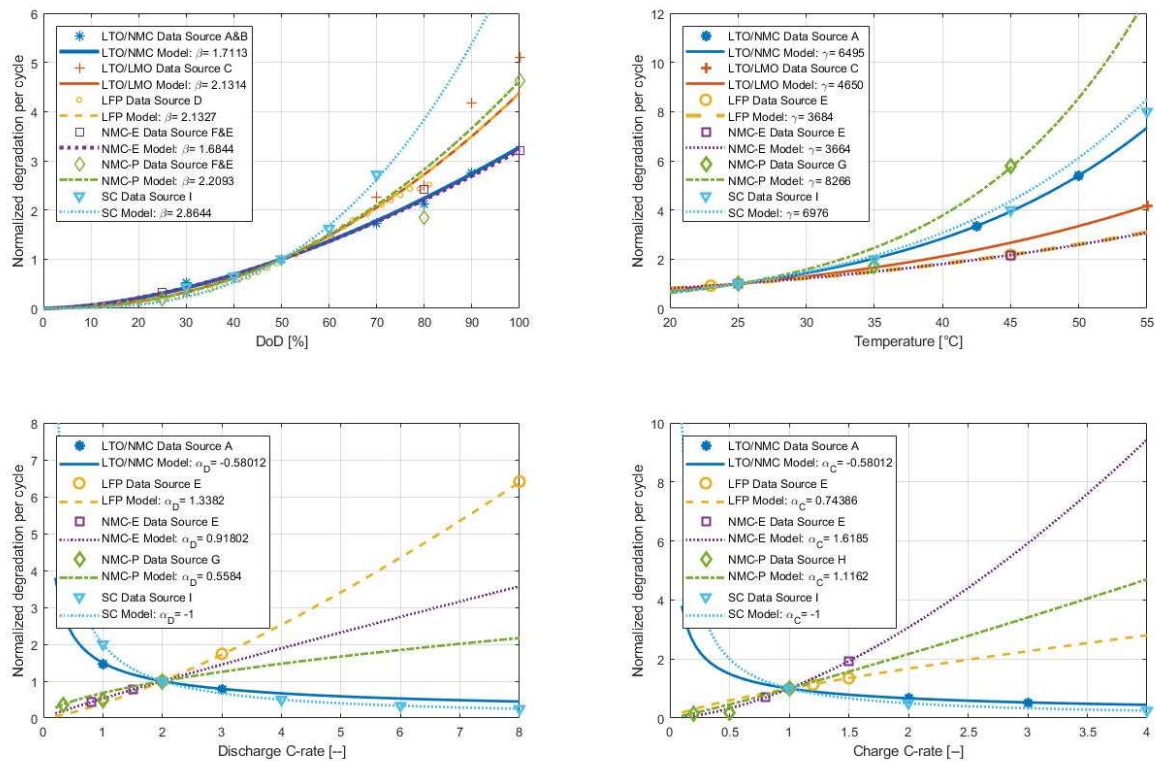


FIGURE 3-5 NORMALIZED DEGRADATION (STRESS FACTOR) PER CYCLE FOR DIFFERENT BATTERY CHEMISTRIES/TECHNOLOGIES AND SUPERCAPACITORS. DATA SOURCES: A= [4], B= [5, 6], C= [7], D= [8], E= [2], F= [11, 12], G= [13], AND H= [14], I= [15, 16, 17].

The main drawback for all degradation models is the availability of cycling performance data for fitting the degradation model parameters, as normally the battery/supercapacitor cell/module manufacturers limit the cycling performance data to one or two datapoints in their product datasheets, and even more, sometimes just including a representative number of cycles to EOL without specifying the reference cycling conditions. The degradation factor parameters for each technology have been calculated using different data sources and they can be considered as representative parameters for each technology when neglecting other factors that may affect the cell degradation performance beyond the anode/cathode chemistry, as for example the shape (cylindrical, pouch or prismatic), the cell size, dimensions, internal number of layers. Cycling performance data reported in [6, 7, 8] have been considered to estimate all stress factor parameters for LTO-NMC technology, while for LTO-LMO technology, data reported in [9] have been used to estimate β and γ , but no data could be found for estimation of α_C and α_D . For LFP technology, cycling performance data reported in [10, 4] has been considered. Also, the data reported in [11, 12, 13, 4] have been considered for the estimation of degradation stress factor parameters of NMC-E and NMC-P technologies. In the case of supercapacitors, their degradation is mainly determined by the amount of time they are kept at a given voltage and temperature [14], so degradation performance data reported in [14, 15] along with a methodology introduced by SKELETON and other reported in [16] have been considered to estimate the supercapacitor degradation stress factor parameters.

FIGURE 3-5 shows the estimated normalized degradation per cycle ($D_{Q.cyc}/D_{Q.cyc.REF}$) for different battery chemistries/technologies and supercapacitor, under reference conditions $DoD_{ref}=50\%$, $I_{C.ref}=1$, $I_{D.ref}=2$, and $T_{C.ref}=25^{\circ}\text{C}$, along with the data sources used to estimate the degradation stress factor fitting parameters. It can be noted, from FIGURE 3-5, that the degradation performance of high-power cells is more affected by high temperatures compared to energy cells, but on the other hand, the higher charge/discharge C-rates creates more degradation stress in energy cells compared to high-power cells. Even more, for very-high-power cells, like LTO-NMC and supercapacitors, the degradation stress reduces as the C-rate increases, which can be related to the fact that faster cycles are achieved at higher C-rates, reducing the time the cell is exposed to a given temperature.

For a given power time series, the rain-flow algorithm has been used to estimate the equivalent energy cycles and their DoDs and C-rates, however the average module/cell temperature cannot be determined directly. The module/cell temperature performance depends on multiple factors, like the ESS cooling system and the module thermal performance. A simplified approach is considered here. First, the average module/cell temperature is proportional to the cell/module losses, which are mainly ruled by the internal resistance, and therefore the losses are proportional to the square of cell/module current rate. Then, by neglecting variations of the internal resistance during the cycle, the module temperature rise against a constant heatsink temperature ($T_{HS.REF}$) is proportional to the square of the current rates ratio.

The average cell/module temperature per cycle (T_C) assumed as average temperature during charge and discharge is approximated by:

$$T_C = T_{HS.REF} + (T_{C.REF} - T_{HS.REF}) \cdot \left[\frac{P_D}{P_D + P_C} \cdot \left(\frac{I_C}{I_{C.Tref}} \right)^2 + \frac{P_C}{P_D + P_C} \cdot \left(\frac{I_D}{I_{D.Tref}} \right)^2 \right]$$

where I_C and I_D are the cycle charging and discharging rates, respectively, P_C and P_D are the equivalent cycle charging and discharging power, respectively, $T_{C.REF}$ is the reference average cell/module temperature per cycle at reference cycle charging and discharging rates, $I_{C.Tref}$ and $I_{D.Tref}$, respectively.

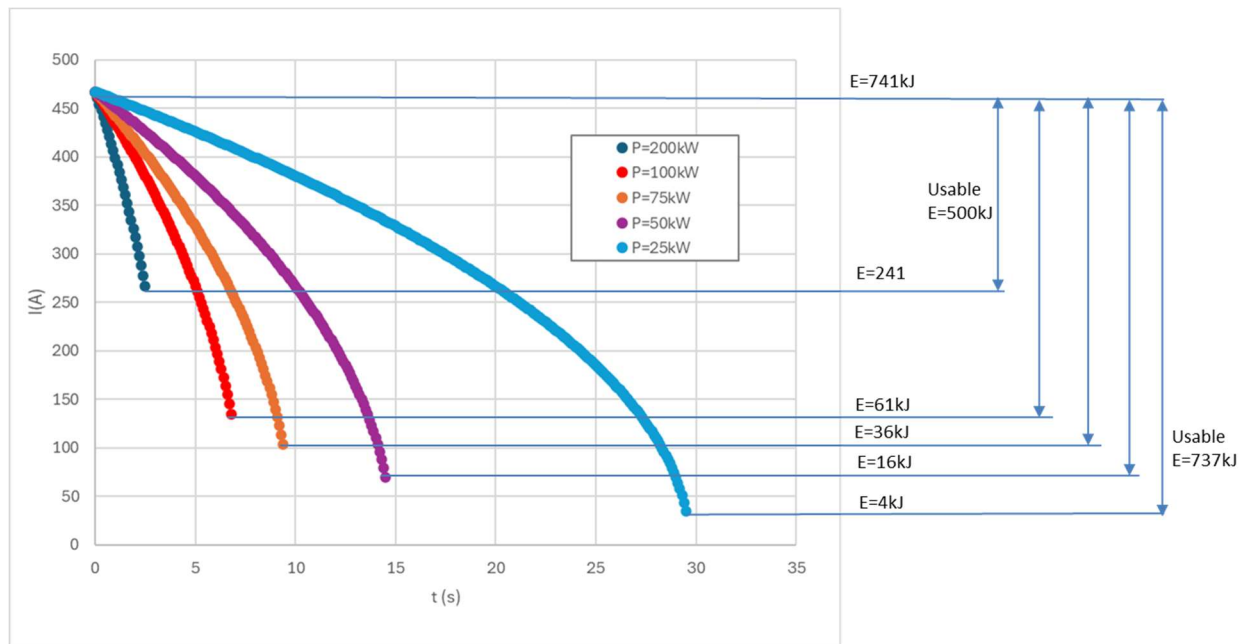


FIGURE 3-6 CONSIDERED SMES CURRENT/POWER CAPABILITY PROFILE AND USABLE ENERGY CORRELATION FOR SMES REFERENCE DESIGN. DATA PROVIDED BY ASG SUPERCONDUCTORS SPA.

For the SMES, only the sizing rules related to power capability and usable energy apply as SMES degradation has been considered negligible. Even more, an extra degree of freedom has been considered for SMES design, considering a correlation between the continuous power capability and the usable energy of the SMES, which follows data provided by manufacturer ASG superconductors SpA. FIGURE 3-6 shows the SMES Current/Power capability profile and usable energy correlation for SMES reference design provided by ASG superconductors SpA.

3.6. Pareto optimality sizing of the energy storage elements

Each potential solution from the power splitting algorithm has different requirements affecting the sizing of individual HE- and HP-ESSs. The potential HESS solutions are compared against the two monotype solutions as ESS based on only one technology (e.g. only NMC battery) in terms of required installed capacity and potential capital cost reduction from core cells. The HESS sizing methodology adopts a graphical approach shown in FIGURE 3-7 for easy comparison, where the potential HESS solutions are represented by plotting the required installed capacity of each subsystem (BESS and HP-ESS).

The HESS installed capacity (Q_{HESS}) is estimated by the sum of the installed energy capacity of HE-ESS or BESS (Q_{HE} or (Q_{BESS})) and the installed energy capacity of HP-ESS (Q_{HP}):

$$Q_{HESS} = Q_{HE} + Q_{HP}$$

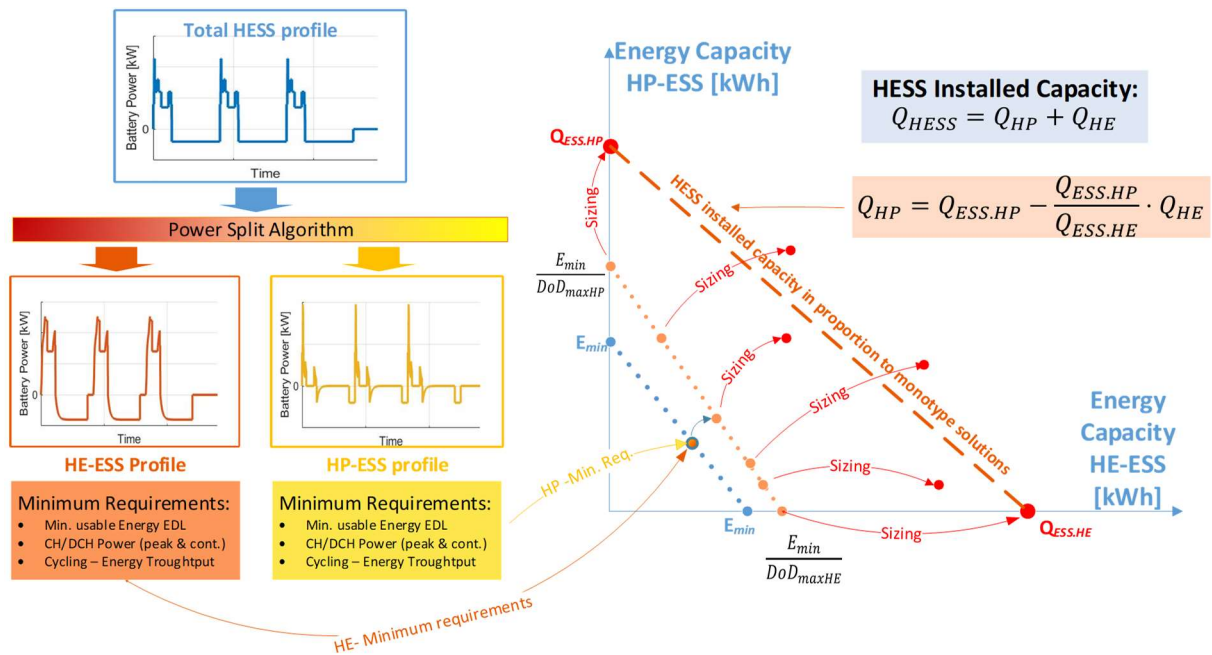


FIGURE 3-7 METHODOLOGY SUMMARY FOR HESS FIRST SCREENING GRAPHICAL REPRESENTATION.

The HESS solution space can be compared against a reference line representing the HESS installed capacity in proportion to the installed capacity of monotype solutions, so a potential gain in required installed capacity can be found if there are solutions which fulfil the following criteria:

$$Q_{HP} < Q_{ESS,HP} - \frac{Q_{ESS,HP}}{Q_{ESS,HE}} \cdot Q_{HE}$$

where, $Q_{ESS,HP}$ is the required installed capacity of a monotype HP-ESS solution, and $Q_{ESS,HE}$ is the required installed capacity of a monotype HE-ESS (or BESS) solution. Accounting for this criterion, a potential case study can be graphically detected based on gains in the required installed energy for the HESS.

FIGURE 3-8 shows an example of graphical representation of potential case studies based on gains in the required installed energy for the HESS. FIGURE 3-8-a and FIGURE 3-8-b show potential case studies, so there are HESS solutions which fulfil the previous presented criterion. However, FIGURE 3-8b, compared with FIGURE 3-8a, shows a less relevant case study, mainly because less solutions fulfil the potential gain in required installed capacity criterion but also because the HESS solutions are characterized by a higher required installed capacity of the HP-ESS compared to the HE-ESS capacity. This could be more costly as the HP-ESS has normally a higher cost per unit energy than the HE-ESS technology. Therefore, HESS solutions with $Q_{HE} \gg Q_{HP}$ will have more potential benefits. On the other hand, FIGURE 3-8-c shows a case when the

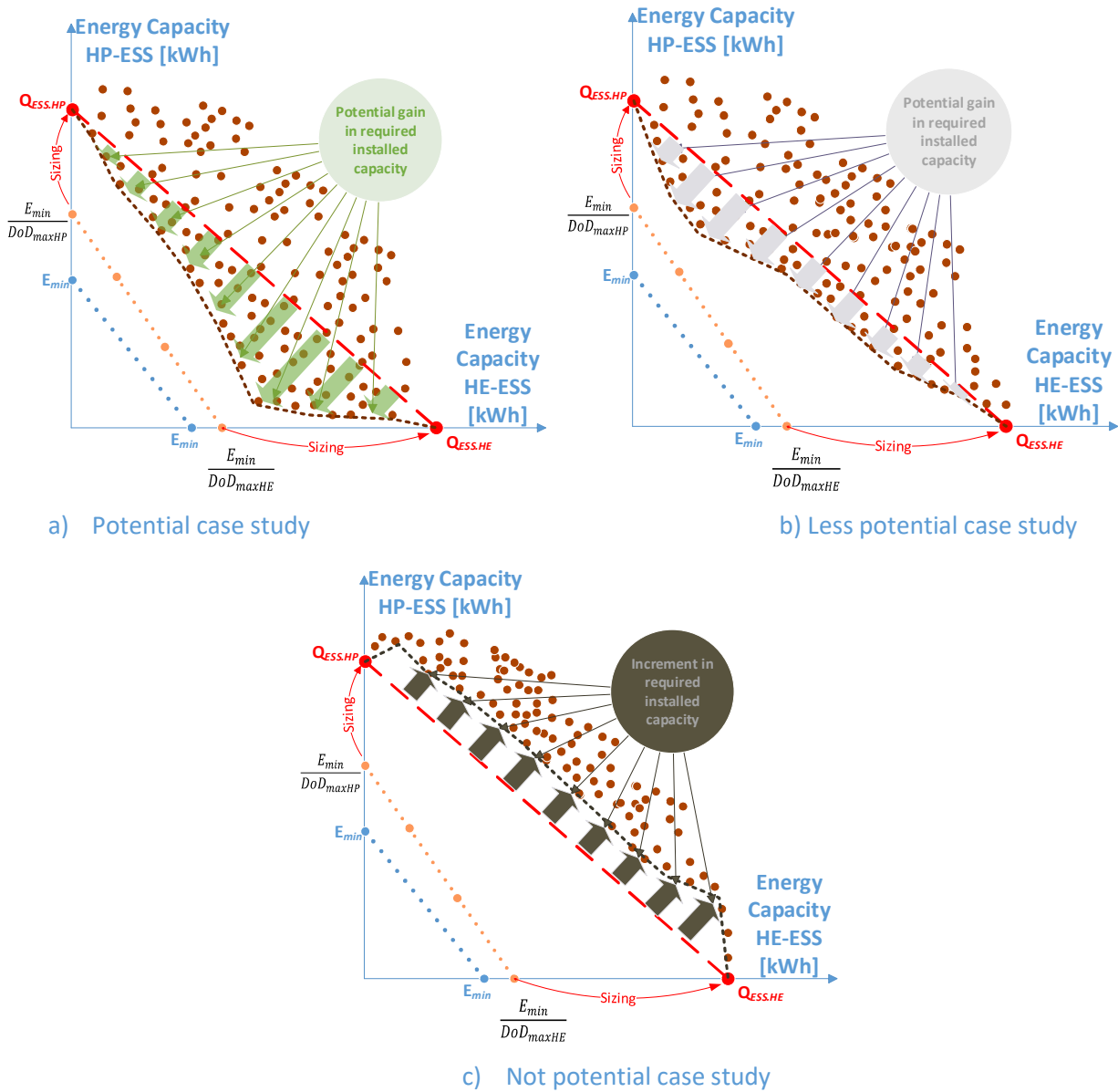


FIGURE 3-8 EXAMPLE OF GRAPHICAL REPRESENTATION OF POTENTIAL CASE STUDIES BASED ON GAINS IN REQUIRED INSTALLED ENERGY FOR HESS.

analysed HESS profile does not represent a potential case of study as there are not HESS solutions which fulfil the potential gain in the required installed capacity criterion.

An additional criterion can be considered by checking if there are HESS solutions with a potential reduction in capital cost of the HESS compared with a monotype BESS. As a first approach, it is proposed to account only for the capital cost related to ESS cell cost, as it normally counts for around 70-80% of total ESS cost. The total cell cost of a HESS solution can be expressed by

$$Cost_{HESS} = Cost_{HE} \cdot Q_{HE} + Cost_{HP} \cdot Q_{HP}$$

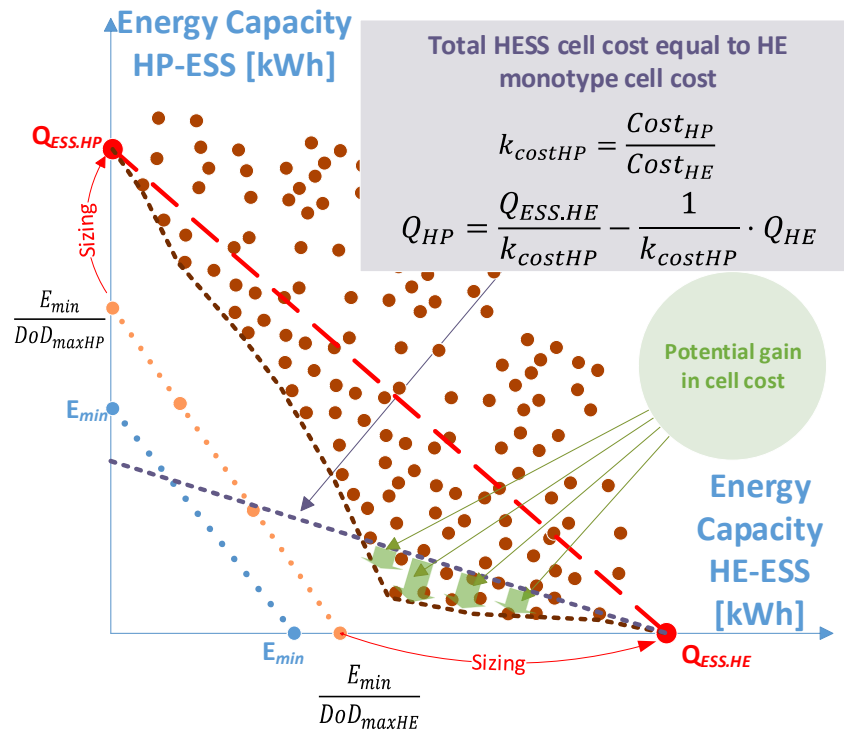


FIGURE 3-9 EXAMPLE OF A HESS POWER PROFILE WITH SOME HESS SOLUTIONS SHOWING POTENTIAL REDUCTION IN CAPITAL COST.

where $Cost_{HE}$ and $Cost_{HP}$ are the cost per unit energy of HE-ESS and HP-ESS cells, respectively. Taking as baseline the cost of a monotype HE-ESS solution, then a potential reduction of HESS solutions against monotype solution can be estimated by checking that the total HESS cell cost is lower than the monotype HE-ESS cell cost, that is finding solutions fulfilling the following criterion:

$$Q_{HP} < \frac{Cost_{HE}}{cost_{HP}} \cdot (Q_{ESS,HE} - Q_{HE})$$

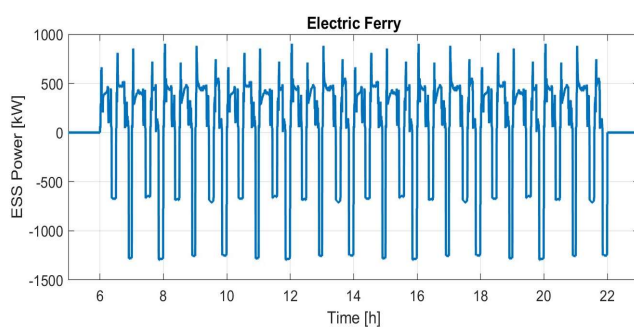
The same procedure can be repeated for HESS volume and weight. FIGURE 3-9 shows an example of a HESS power profile with HESS solutions showing potential reduction in capital cell cost. It should be mentioned that even though there is not a potential reduction in HESS cost, volume of weight compared with BESS-only solution, it still could be potential benefits not considered in this assessment, especially related to the overall system efficiency. For example, the increasing of the ESS efficiency could bring additional economic benefits not only associated to reduced energy charged from shore or extension of the vessel range in full electric systems, but also related to increment of the vessel Energy Efficiency Design Index (EEDI) and associated reductions on vessel fuel consumption and emissions in hybrid marine power systems. The ESS energy efficiency is analysed in WP3/WP4 and therefore has not been considered within WP1 assessment.

4. Electric Ferry Case

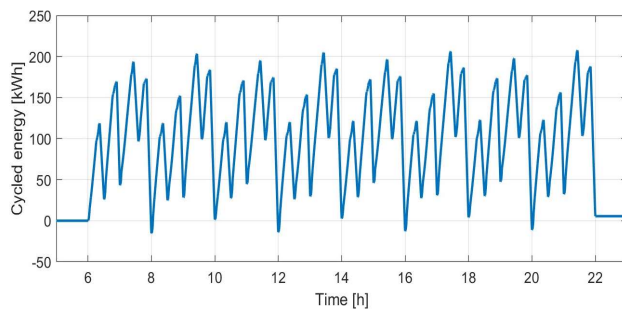
4.1. Mission Profile and General Specifications

The case assumes a full electric ferry (74m length x 15 m width) with a symmetrical (redundant) electric power system including two identical BESS as main energy source (2x678 kWh G/NMC-P Orca Energy from Corvus Energy see appendix A.1). The single line diagram is presented in FIGURE A-1 (Appendix A.2). The mission power profile is based on logged data provided by Vard Electric (see appendix A.3) with:

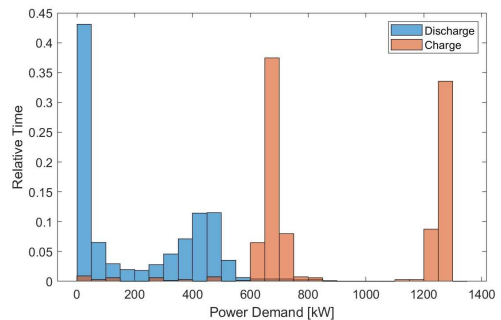
- No seasonal variations and 320 operating days per year: (to match with reference BESS-(NMC-P)).
- Operation hour: 06:00-22:00 (16 hours). Four fundamental cycles per day, 16 turn/return trips per day between stops A and B.
- Log data fundamental Cycle length: 2 hours (2 turn/return trips). ESS fundamental Cycle length: 4 hours (4 turn/return trips) – combination of the two ESS log data fundamental cycles.
- Sampling period: 6 seconds



a) Profile time series (typical operational day)



b) Aggregated power profile



c) Profile RMS power

FIGURE 4-1 ELECTRIC FERRY: STANDARD MISSION PROFILE PER ESS. REDUNDANT ELECTRIC SYSTEM WITH 2 IDENTICAL ESS.

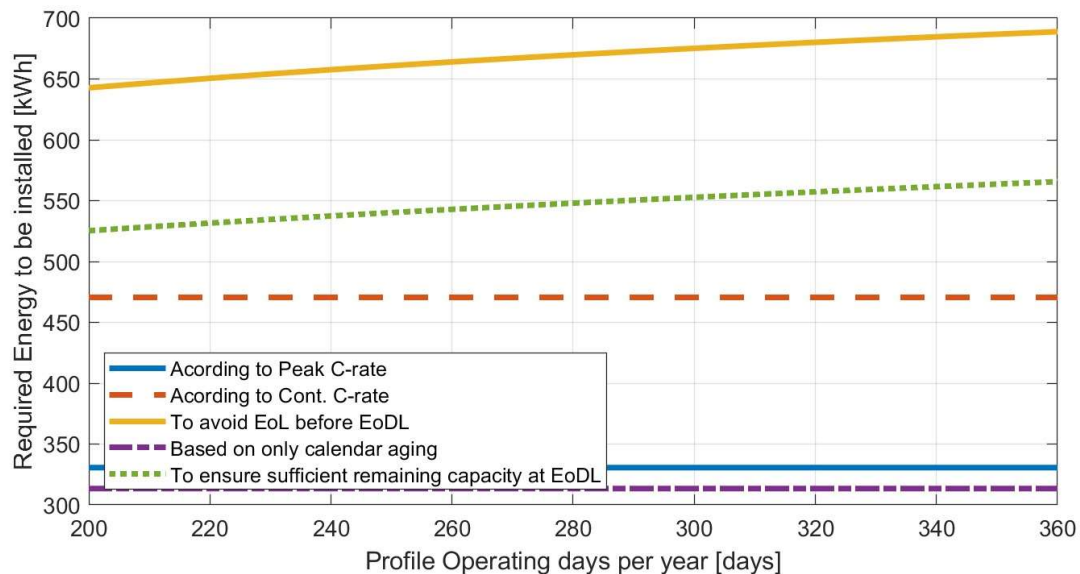


FIGURE 4-2 REQUIRED BESS ENERGY TO BE INSTALLED FOLLOWING DIFFERENT ESS SIZING CRITERIA VERSUS OPERATING DAYS PER YEAR. ELECTRIC FERRY CASE PROFILE CONSIDERING THE REFERENCE NMC-P BESS TECHNOLOGY.

- 1.3 MW charging station at Stop A (max. charging 675 kW per ESS) and 2.4 MW Charging Station at stop B (max. charging 1290 kW per ESS).

FIGURE 4-1 shows the electric ferry standard mission profile per ESS considered in this work.

From the considered electric ferry standard mission profile, the following requirements per ESS can be derived:

- Minimum needed energy: 223 kWh
- Max. discharge power: 903 kW (peak), 671 kW (cont.)
- Max. charge power: 1300 kW (peak), 1292 kW (Cont.)
- Energy throughput: 1292 MWh
- Equivalent Active days per year: 213.33 days

The operating days per year have been determined so that the sizing estimation from the proposed BESS sizing algorithm matches the reference battery system (see appendix A.3) with the same BESS technology (NMC-P). FIGURE 4-2 shows the estimated BESS Energy to be installed following the different ESS sizing criteria (introduced in section 3.5) versus profile operating days per year and for the NMC-P battery technology with performance parameters introduced in TABLE 3. It can be noted that a BESS based on NMC-P technology needs to be sized to avoid End-of-Life before the End-of-Design-Life (10 years). This can be related to high cycling degradation associated to the high continuous C-rates required by the profile (especially for the cont. charging rates).

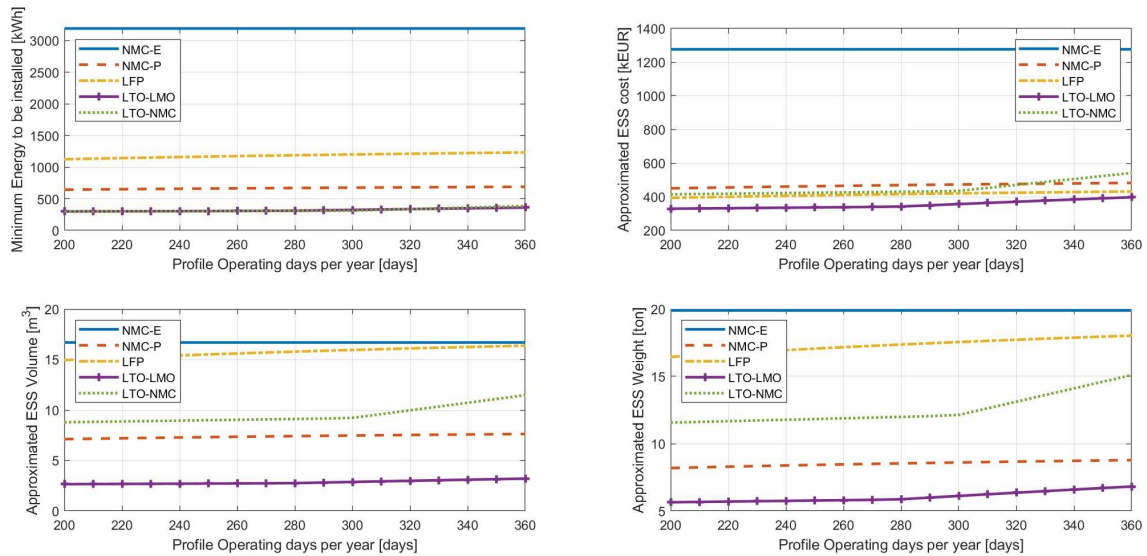


FIGURE 4-3 ELECTRIC FERRY CASE: BESS SIZING RESULTS AGAINST PROFILE OPERATING DAYS PER YEAR FOR DIFFERENT BATTERY TECHNOLOGIES/CHEMISTRIES.

4.2. Optimal BESS solution

The ESS sizing for electric ferry case has been estimated for all the considered battery technologies to establish the optimal BESS solution in this case. FIGURE 4-3 shows the BESS sizing results against a profile operating days per year for different Battery technologies/chemistries.

It can be observed that the LTO-LMO technology provides the best performance for this application. It is important to note that this result is for the specific ferry mission profile considered in this work and not for electric ferries in general, as sizing results will change if minimum energy per trip changes or if reduced charging power (longer charging time) is allowed. TABLE 4 summarizes the main BESS sizing results for

TABLE 4 ELECTRIC FERRY CASE: BESS-ONLY SIZING RESULTS.

Technology	NMC-E	NMC-P	LFP	LTO/LMO	LTO/NMC
Required Energy [kWh]	3190	679.5	1211	335	335.7
BESS Cost [k€]	1276	476	424	368	470
BESS Volume [m³]	16.69	7.52	16.11	2.98	9.97
BESS Weight [Tons]	19.89	8.66	17.72	6.33	13.12
SOH at EoDL [%]	90.3	80	80	80	80
Sizing Criteria	According to Cont. C-rate	To Avoid EoL before EoDL			

different battery technologies/chemistries, when 320 operating days per years are considered. It can be noted that NMC-E BESS needs to be sized following the continuous C-rate requirement for this application, showing a clear case of oversizing because of the power capability requirements.

4.3. HESS-EMS design space and multi-dimensional subspace requirements

The first task in the HESS sizing algorithm is to map the multi-dimensional subspace of requirements for the HE-ESS and HP-ESS from the considered HESS-EMS design space. The HESS-EMS design space is composed by the low pass filter cut-off frequency, the maximum discharge power of HE-ESS and the charging strategy as presented in section 3.4. FIGURE B-1, in appendix B.1, shows the amplitude Spectrum of ferry power profile, which help to determine an appropriate range for the low pass filter frequencies. For the ferry profile, the filter frequency is swept between 1 μ Hz and 1dHz, besides 0 and infinite, which are related to monotype solutions. For the filter discharge power limit, values between 300 kW and 903kW have been considered. FIGURE 4-4 shows the mapped multi-dimensional subspace requirements for HE-ESS and HP-ESS when prioritizing HP-ESS charge during HESS charge state is selected as EMS charging strategy.

The colour code in each graph represents the magnitude of the requirement stated in the title of the plot. For example, for the top-left plot in FIGURE 4-4, the minimum required energy for the HE-ESS is shown against the HESS-EMS parameters (low pass filter cut-off frequency, the maximum discharge power of HE-ESS), and yellow tonnes are related to higher energy requirements, so using higher filter frequencies end up in more energy required for the HE-ESS, as expected. FIGURE 4-4 can be used to detect the relevant

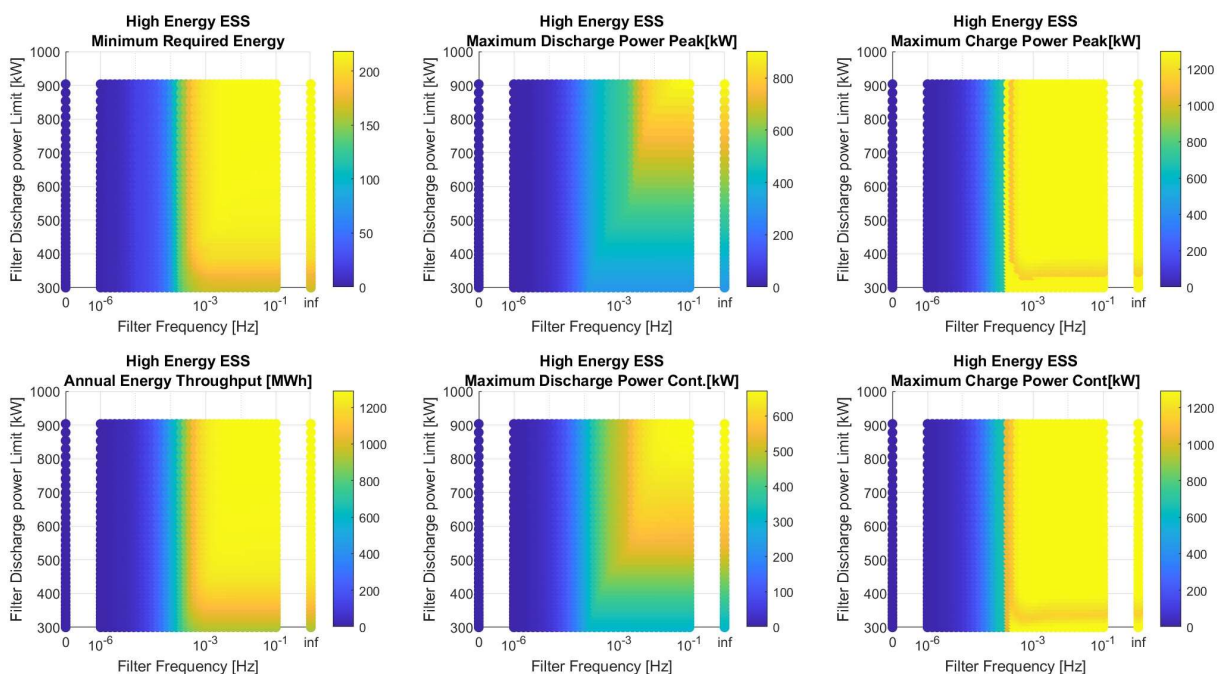


FIGURE 4-4 ELECTRIC FERRY CASE: HESS-EMS DESIGN SPACE MAPPED TO MULTI-DIMENSIONAL SUBSPACE REQUIREMENTS. EMS CHARGING STRATEGY: PRIORITIZING HP-ESS CHARGE DURING HESS CHARGE STATE.

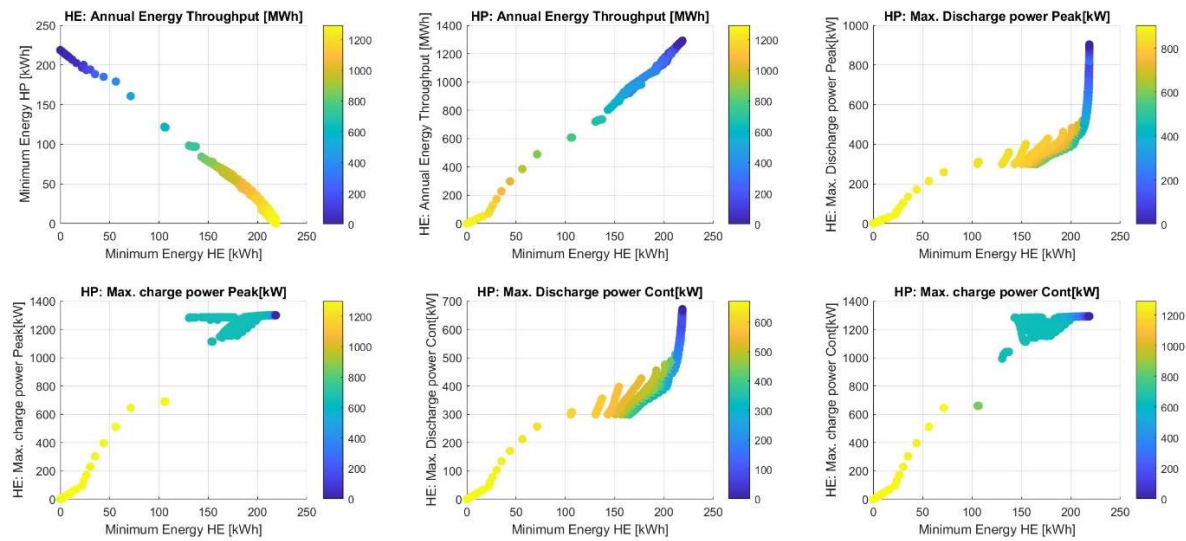


FIGURE 4-5 ELECTRIC FERRY CASE: CORRELATION BETWEEN HESS-EMS MAPPED MULTI-DIMENSIONAL SUBSPACE REQUIREMENTS. EMS CHARGING STRATEGY: PRIORITIZING HP-ESS CHARGE DURING HESS CHARGE STATE.

parameters, so the algorithm search could be limited to find relevant solutions with higher energy requirements for the HE-ESS and higher power requirements for the HP-ESS.

FIGURE 4-5 shows the correlation between the mapped multi-dimensional subspace requirements, for the same HESS design space of FIGURE 4-4 (EMS charging strategy: Prioritizing HP-ESS charge during HESS charge state). It can be noted that the max peak/cont. discharge power requirement for HE-ESS can be reduced while keeping high HE minimum/usable energy (using the HP-ESS to supply the discharge peaks) but not for the charge power. This fact could be a limiting factor to get optimal solutions for HESS, as the charging power rate for the HE-ESS cannot be reduced.

For the sake of completeness, FIGURE B-4 and FIGURE B-5, in appendix B.1, show the correlation between the mapped multi-dimensional subspace requirements for the other two EMS charging strategies. By comparing those figures with FIGURE 4-5, it can be noted that in this case the ESS requirements can be slightly changed by changing the EMS charging strategy.

It should be noted that this step is independent of the ESS technology, so common for any combination of BESS technologies with HP-ESS technologies (SC/SMES). Technology performance is evaluated within the ESS sizing algorithm in the next step.

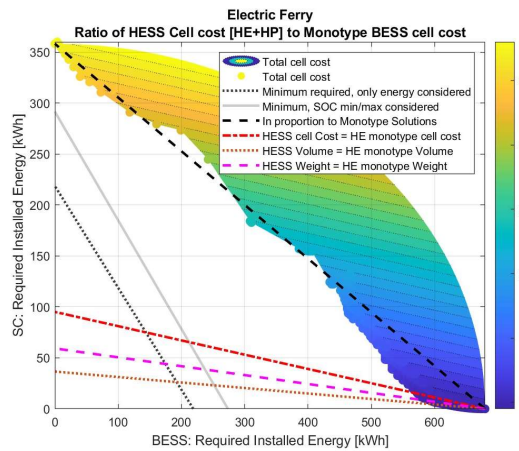
4.4. HESS solution: Combination of BESS and Supercapacitors

Results for HESS solutions based on batteries combined with supercapacitors are presented in this section. Combination of SC with all battery technologies/chemistries from [TABLE 3](#) have been checked but only two combinations are reported in this section: NMC-P batteries with SC and LTO-LMO batteries with SC. NMC-P batteries are considered as it is the technology of Electric Ferry reference battery system provided by VE (see appendix A.1). On the other hand, LTO-LMO batteries provide the best BESS system for the considered ferry profile. Results for other battery technologies can be found in appendix B.1. Although the combination of NMC-E (very high energy dense) with SC may seem a good alternative, the benefit of using SC is limited by the high charge power requirement, keeping the NMC-E BESS sized according to charge power as in the BESS-only case.

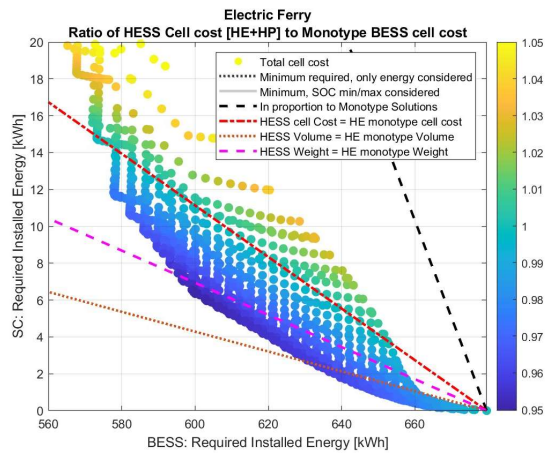
FIGURE 4-6 reports the main HESS sizing results for combination of Li-ion NMC-P Batteries and Supercapacitors and when the EMS charging strategy is to prioritize SC charge during HESS charge state (which is the best charging strategy along the other two strategies for this case). Results for other charging strategies can be found in the appendix B.1 (FIGURE B-8 and FIGURE B-9).

FIGURE 4-6a shows the full required energy performance space (required BESS energy versus required SC energy), along with the reference lines for solutions with same cost, volume, and weight as the BESS-only solution. Each point in FIGURE 4-6a represents a possible solution (combination of BESS and SC) associated to the pair of EMS parameters (filter frequency and BESS max. discharge power). The colour code for FIGURE 4-6a represents the HESS cost for each solution. It can be noted that the SC-only solution will require around 360 kWh installed SC energy. Also, it can be noted that the most relevant solutions are for combinations with reduced installed SC energy.

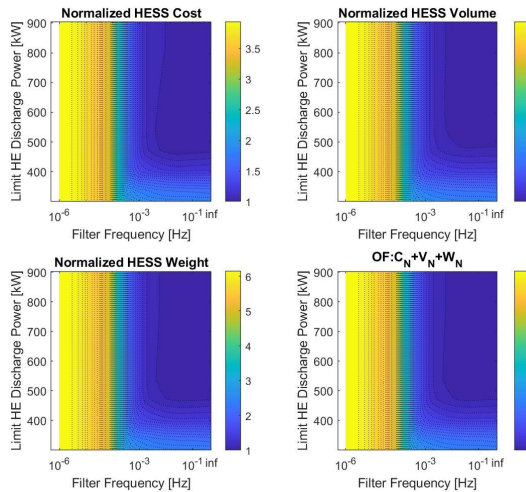
FIGURE 4-6b shows a zoom of required energy performance space in the relevant range (for SC installed energy <20kWh). Solutions with less than 2 kWh SC energy will reduce cost, volume and weight compared with an NMC-P BESS-only solution. FIGURE 4-6d shows the energy pareto for NMC-P and SC along with the normalized HESS cost, volume and weight evaluated for the energy pareto. It can be noted that there is not a single solution to minimize all the performance indices at the same time, but also it can be noted that the best solutions are for SC energy less than 6 kWh, which represents a maximum BESS energy reduction of 80kWh (from 680 kWh to 600kWh). FIGURE 4-6c shows the HESS-EMS design space mapped to HESS performance space.



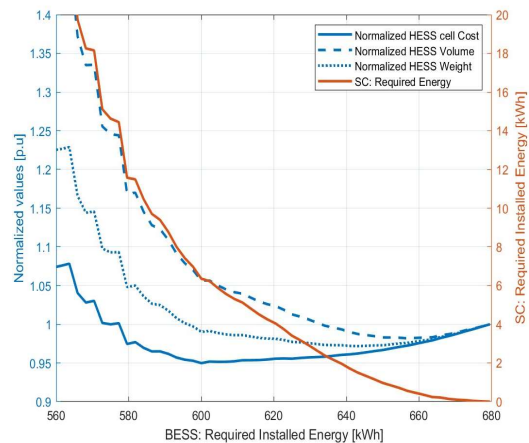
A. Full Required Energy performance space



B. Performance space zoom for SC installed energy <20kWh



C. HESS-EMS Design Space mapped to performance space

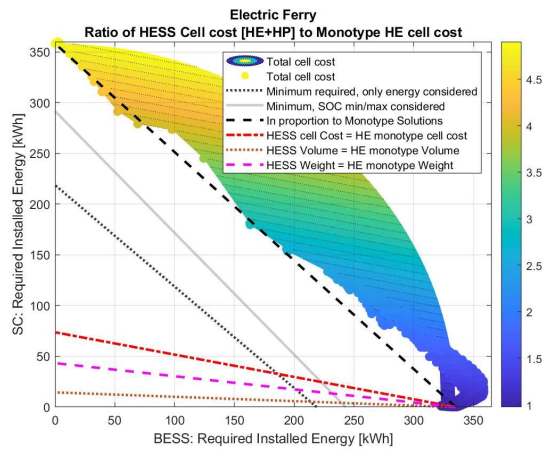


D. Required SC energy, HESS cost, volume and weight pareto optimalities versus required BESS installed energy

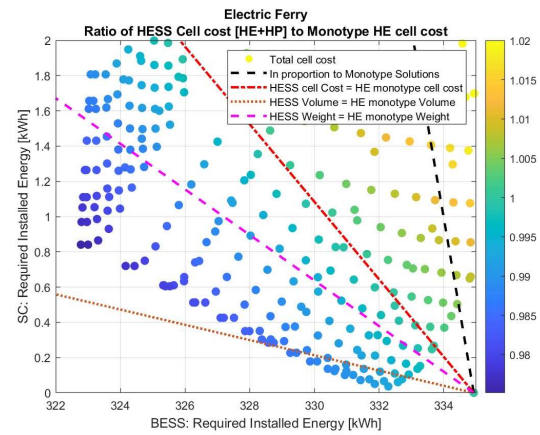
FIGURE 4-6 ELECTRIC FERRY CASE: HESS SIZING RESULTS FOR COMBINATION OF LI-ION NMC-P BATTERIES AND SUPERCAPACITORS. EMS CHARGING STRATEGY: PRIORITIZING HP-ESS CHARGE DURING HESS CHARGE STATE.

FIGURE 4-7 reports the main HESS sizing results for combination of Li-ion LTO-LMO Batteries and Supercapacitors and when EMS charging strategy is to force SC charge during HESS discharge state (which is the best charging strategy along the other two strategies for this case). Results for other charging strategies can be found in the appendix B.1 (FIGURE B-8 and FIGURE B-9).

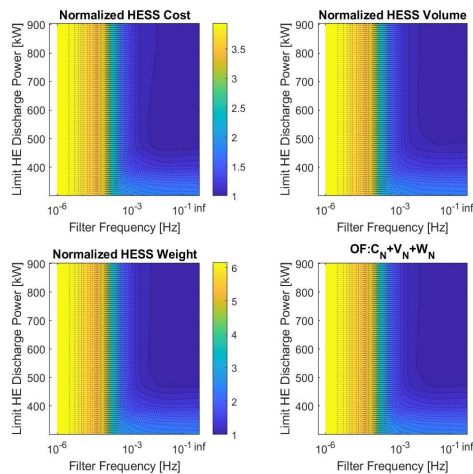
Similarly to the previous figure, FIGURE 4-7a shows the full required energy performance space (required BESS energy versus required SC energy). It can be noted that in this case, the combination with SC does not bring good margins in performance. Compared with previous case, the relevant solutions are limited to SC



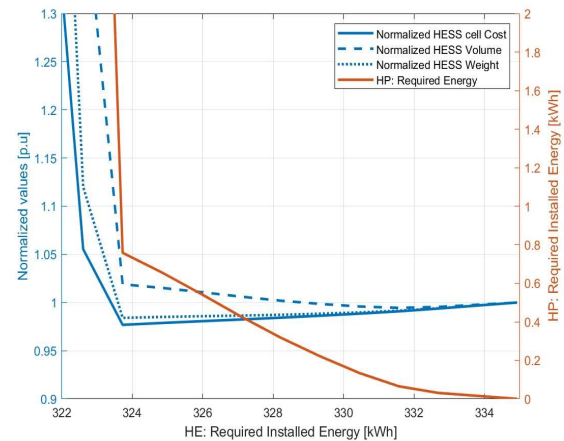
a) Full Required Energy performance space



b) Performance space zoom for SC installed energy <2kWh



c) HESS-EMS Design Space mapped to performance space



d) Required SC energy, HESS cost, volume and weight pareto optimalities versus required BESS installed energy

FIGURE 4-7 ELECTRIC FERRY CASE: HESS SIZING RESULTS FOR COMBINATION OF LI-ION LTO-LMO BATTERIES AND SUPERCAPACITORS. EMS CHARGING STRATEGY: FORCING HP-ESS TO FULLY CHARGE DURING HESS DISCHARGING STATE.

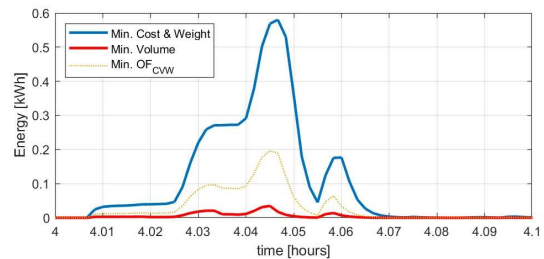
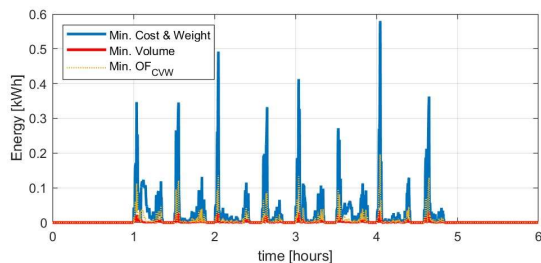
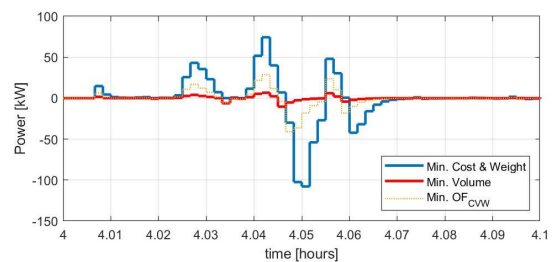
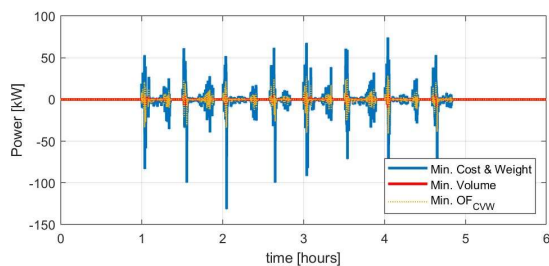
energy less than 1 kWh, as can be noted from FIGURE 4-7b and FIGURE 4-7d. The energy pareto optimality faces a wall when the LTO-LMO energy is reduced below around 324 kWh, with a corner in around 0.8kWh for SC energy. HESS cost and weight can be slightly reduced compared with LTO-LMO BESS-only solution; however, the volume slightly increases.

TABLE 5 summarizes the best HESS solutions when the BESS is combined with a SC. Each column at TABLE 5 is a selected solution regarding minimum HESS cost, volume, weight, or a combination of those represented in the objective function OF_{CVW} . The BESS-only solutions, from TABLE 4, are also added for the sake of completeness and comparison. It can be noted that the best NMC-P solutions cannot reduce the performance of the BESS-only solution based on LTO-LMO (which values are highlighted in bold).



TABLE 5 ELECTRIC FERRY CASE: HESS SIZING RESULTS FOR BESS COMBINED WITH SC.

<i>Solution Target:</i>	BESS-only	Min. Cost	Min. Volume	Min. Weight	Min. OF _{CVW}	BESS-only	Min. Cost	Min. Volume	Min. Weight	Min. OF _{CVW}	
<i>BESS technology:</i>	NMC-P					LTO-LMO					
<i>Required Energy [kWh]</i>	BESS	679.5	600.04	655.75	639.66	644.06	335	322.91	332.29	322.91	329.27
	SC	---	6.346	0.609	1.792	1.416	---	0.861	0.0514	0.861	0.252
<i>HESS Cost [k€]</i>		476	451.76	462.07	456.72	457.92	368	359.5	365.36	359.5	363.04
<i>HESS Volume [m³]</i>		16.69	7.948	7.386	7.451	7.422	2.98	3.050	2.967	3.050	2.982
<i>HESS Weight [Tons]</i>		19.89	8.574	8.445	8.413	8.414	6.33	6.229	6.288	6.229	6.260
<i>HESS-EMS charging Strategy</i>	----	Prioritizing HP-ESS charge during HESS charge state					--	Forcing HP-ESS to fully charge during HESS discharging state			



a) Fundamental Ferry profile cycle

b) Zoom when SC peak energy is reached.

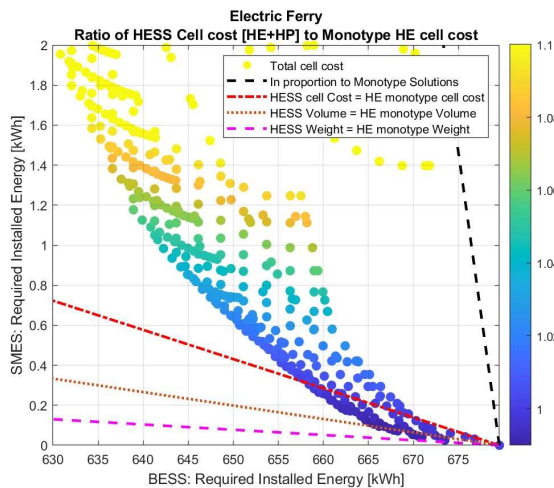
FIGURE 4-8 ELECTRIC FERRY CASE: SC WAVEFORMS OF THE HESS SELECTED SOLUTIONS FOR COMBINATION OF LI-ION LTO-LMO BATTERIES AND SUPERCAPACITORS.

Combination of SC with LTO-LMO batteries can bring solutions with lower HESS cost and weight while with similar volume compared with the best BESS-only solution. It can be noted that the solutions with the lowest cost and weight are the same.

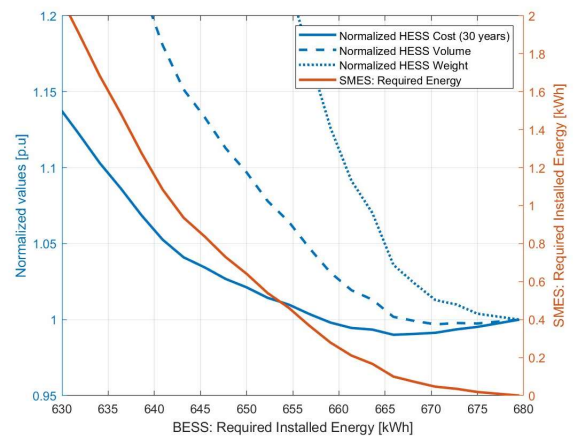
FIGURE 4-8 shows the SC waveforms of the HESS selected solutions for combination of Li-ion LTO-LMO Batteries and Supercapacitors, for the ferry fundamental cycle (FIGURE 4-8a) and a zoom when SC peak energy is reached (FIGURE 4-8b).

4.5. HESS solution: Combination of BESS and SMES

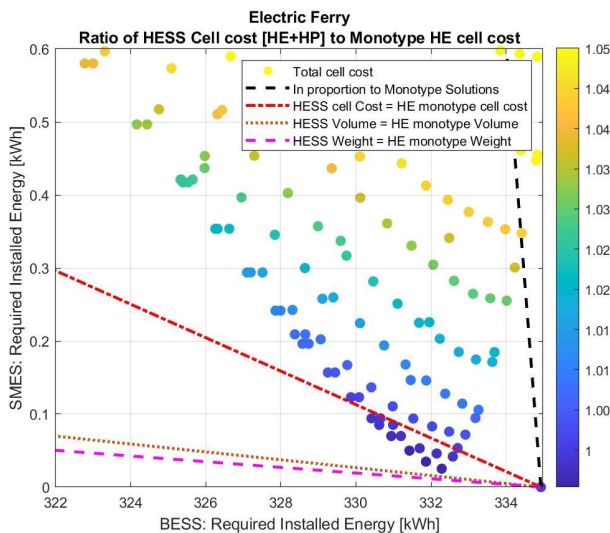
Similar procedure as for previous case was followed for the HESS solution combining BESS with SMES. However, for the case of SMES, the HESS cost is evaluated against the ship lifetime (30 years), instead of the ESS design life (10 years), as the SMES degradation is negligible. Thus, the total cost of the HESS solution will include the BESS replacements to the ship lifetime (3 replacements), and therefore the reference cost of BESS-only solution will be three times the reported cost in TABLE 4.



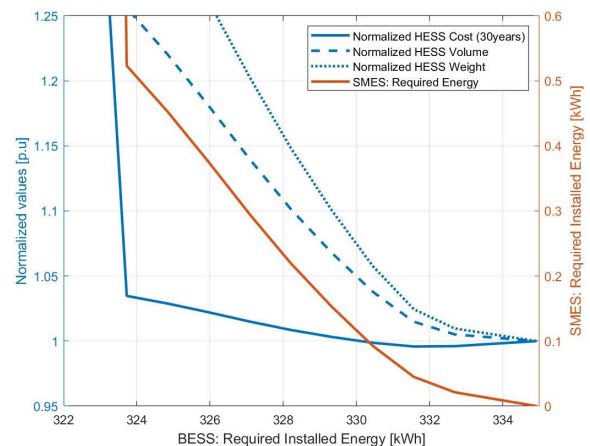
a) Relevant required Energy performance space for HESS combination of NMC-P with SMES



b) Required SC energy, HESS cost, volume and weight pareto optimalities for combination of NMC-P with SMES



c) Relevant required Energy performance space for HESS combination of LTO-LMO with SMES



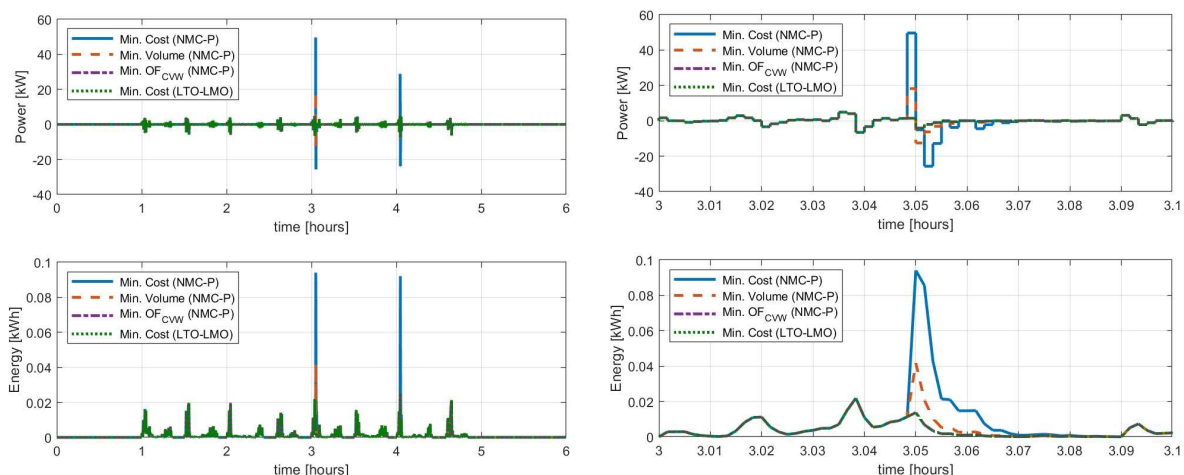
d) Required SC energy, HESS cost, volume and weight pareto optimalities for combination of LTO-LMO with SMES

FIGURE 4-9 ELECTRIC FERRY CASE: HESS SIZING RESULTS FOR COMBINATION OF LI-ION BATTERIES WITH SMES. EMS CHARGING STRATEGY: FORCING HP-ESS TO FULLY CHARGE DURING HESS DISCHARGING STATE.

FIGURE 4-9 shows the HESS sizing results for combination of Li-ion NMC-P and LTO-LMO Batteries with SMES, assuming SMES forced to fully charge during HESS discharging state as EMS charging strategy. For SMES combined with NMC-P batteries, some solutions reduce the HESS cost/volume but slightly increase the HESS weight as can be noted from FIGURE 4-9a, and FIGURE 4-9b. However, when LTO-LMO batteries are combined with SMES, there are only HESS solutions that reduce the cost but not the volume or weight. TABLE 6 summarizes the best HESS solutions when BESS combined with SMES. It can be noted that the best NMC-P solutions cannot reduce the performance of the BESS-only solution based on LTO-LMO. The combination of SMES with LTO-LMO batteries can bring solutions with lower HESS cost but more volume and weight compared with the best BESS-only solution.

TABLE 6 ELECTRIC FERRY CASE: HESS SIZING RESULTS FOR BESS COMBINED WITH SMES.

<i>Solution target:</i>		BESS-only	Minimum Cost	Minimum Volume	Minimum OF_{cw}	BESS-only	Minimum Cost
<i>BESS technology</i>		NMC-P				LTO-LMO	
<i>Required Energy [kWh]</i>	BESS	679.5	666.2	670.95	673.49	335	332.28
	SMES	0	0.0945	0.0419	0.0252	0	0.0252
<i>HESS Cost (30 years) [M€]</i>		1.4270	1.4126	1.4150	1.4179	1.1053	1.1002
<i>HESS Volume [m³]</i>		7.524	7.532	7.498	7.499	2.976	2.994
<i>HESS Weight [Tons]</i>		8.66	8.949	8.754	8.705	6.3285	6.4007
<i>HESS-EMS charging Strategy</i>		Forcing HP-ESS to fully charge during HESS discharging state					



a) Fundamental Ferry profile cycle

b) Zoom when SC peak energy is reached.

FIGURE 4-10 ELECTRIC FERRY CASE: SMES WAVEFORMS OF THE HESS SELECTED SOLUTIONS FOR COMBINATION OF BATTERIES WITH SMES.

FIGURE 4-10 shows the SMES waveforms of the HESS selected solutions for combinations of Li-ion Batteries and SMES, for the ferry fundamental cycle (FIGURE 4-10a) and a zoom when SMES peak energy is reached (FIGURE 4-10b).



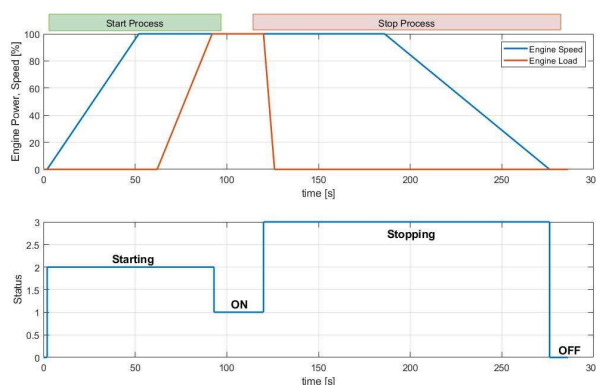
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5. Offshore Support Vessels with Active Heave Compensation System

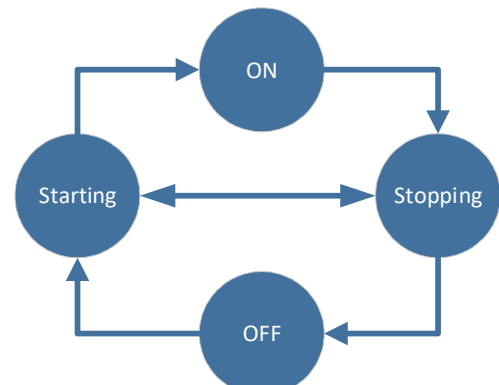
5.1. Mission Profile and General Specifications

The case assumes an Offshore Support Vessels with Active Heave Compensation System. The OSV electrical system is a hybrid marine power system composed of three identical diesel generators rated 2.457 MW. The SDL diagram for OSV is presented in FIGURE A-2 (Appendix A.2). The diesel generator fuel consumption follows a scaled version of the SFC curve provided by Vard Electric, reported in Figure A 7, appendix A.4. Additional specifications are:

- The simulated genset Start and Stop process is presented in FIGURE 5-1 with parameters listed below.
 - Start process parameters:
 - Speed ramp up time: 50 s (from 0 to 100% nominal speed).
 - Synchronization time: 10s
 - Load ramp up time: 30s (from 0 to 100% load)
 - Stop process parameters:
 - Load ramp down time: 6s (from 100% to 0)
 - Idling time: 60s
 - Speed ramp down time: 90s (from 100% nominal speed to 0).
- Focus for ESS analysis is to provide support to the generators during DP level 2 (DP2) operation. Redundance operation is mandatory for DP2 operation without ESS support, so at least two generators should be running all the time. A genset reserve margin of 30% is assumed for redundance genset operation, meaning that a new genset should be turned-on if the actual load of running generators reaches 70% of the maximum available gensets power capacity.



a) Start and Stop process



b) Generator Status State machine

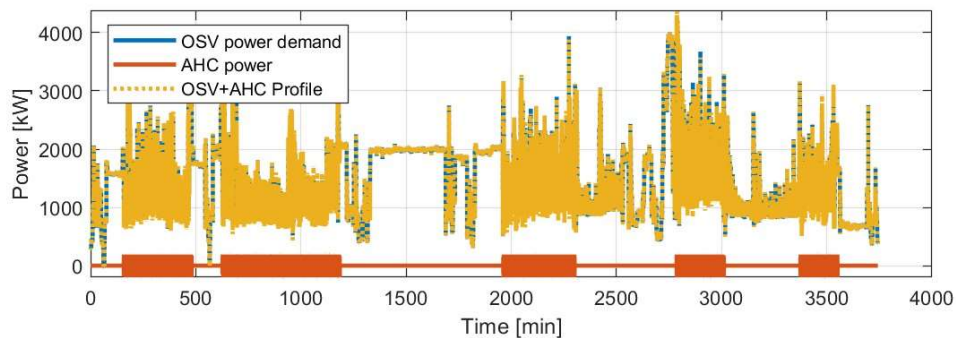
FIGURE 5-1 OSV-AHC CASE: GENSET SIMULATED CHARACTERISTICS.



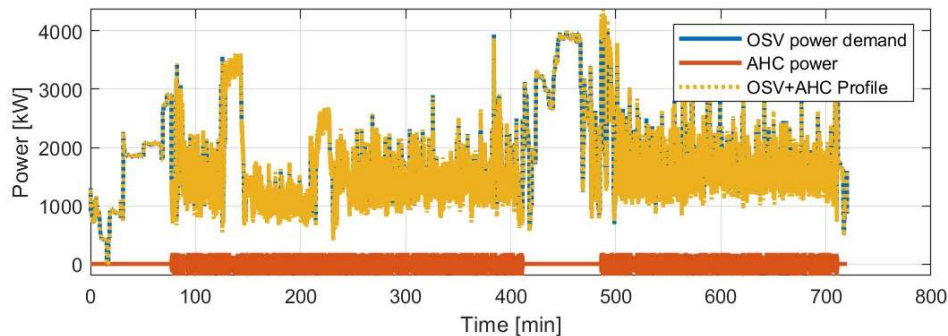
- The following requirements are considered when ESS is designed to be used as spinning reserve:
 - Minimum spinning reserve time: 10 minutes
 - Minimum charging time after Spinning reserve energy used: 20 minutes.
 - Expected number of times per year Spinning reserve will be used: 24.
- It is considered an average efficiency for ESS charging and discharging of 96% and 97%, respectively. The analysis considers the main switchboard as reference point. So, assuming the same voltage at the main switchboard, then higher voltage at the ESS side is needed for discharging than for charging, for the same power this means higher current and lower efficiency for charge than for discharge process. Also, for batteries, normally the equivalent series resistance is higher during charge than discharge process, so more internal losses for charge could be expected.

The profile power series is based on the following assumptions:

- The OSV power demand is based on log data provided by Vard Electric for a platform support vessel (PSV), which includes vessel dynamic position operation. The reference PSV log data is presented in



a) Reference 62 hours series



b) Equivalent 12 hours series.

FIGURE 5-2 OSV-AHC STANDARD MISSION PROFILE.

appendix A.4, FIGURE A-6. The original log data length is 13 days with a sample rate of 15 seconds.

- The AHC system for the specified OSV has been simulated by SINTEF Ocean. An example of AHC simulation profile is presented in appendix A.4, FIGURE A-8.
- SINTEF Ocean has analyzed the PSV log data to perform the AHC simulation during DP mode, so they proposed a power time series for OSV of 62 hours length including AHC power component. FIGURE 5-2a shows the reference 62 hours power time series provided by SINTEF Ocean. The original log data has been resampled to 1 second.
- To reduce the computational time associated with the multi-parametric ESS and HESS sizing algorithm, the reference 62 hours power time series has been analyzed and an equivalent 12-hours power time series has been proposed, which has the same maximum RMS power for time windows lower than 20 minutes, as well as similar short-term power variations, as can be observed from FIGURE B-10, appendix B.2.
- Assumed profile operation:
 - Operating days per year: 219 days

5.2. Reference marine power system operation

To establish a reference operation performance and quantify the benefits of including an ESS in the system, in a first place, the OSV-AHC operation without ESS has been analysed. FIGURE 5-3 shows the considered reference operating rules without installed ESS. For the reference operation, it is assumed that the OSV is in DP2 mode with the load profile in FIGURE 5-2b, so the reference operation rule is the one for redundancy operation and 30% reserve margin in FIGURE 5-3.

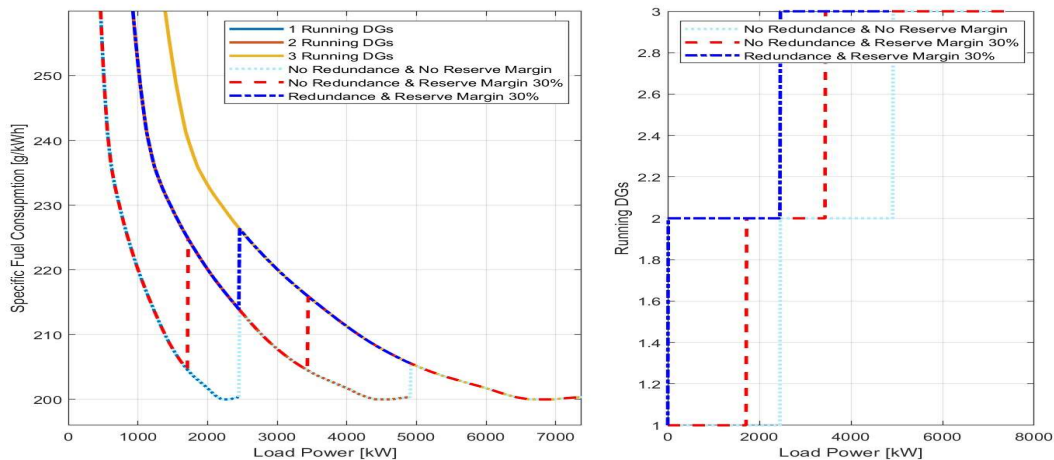


FIGURE 5-3 OSV-AHC CASE: REFERENCE OPERATING RULES WHEN NO INSTALLED ESS.

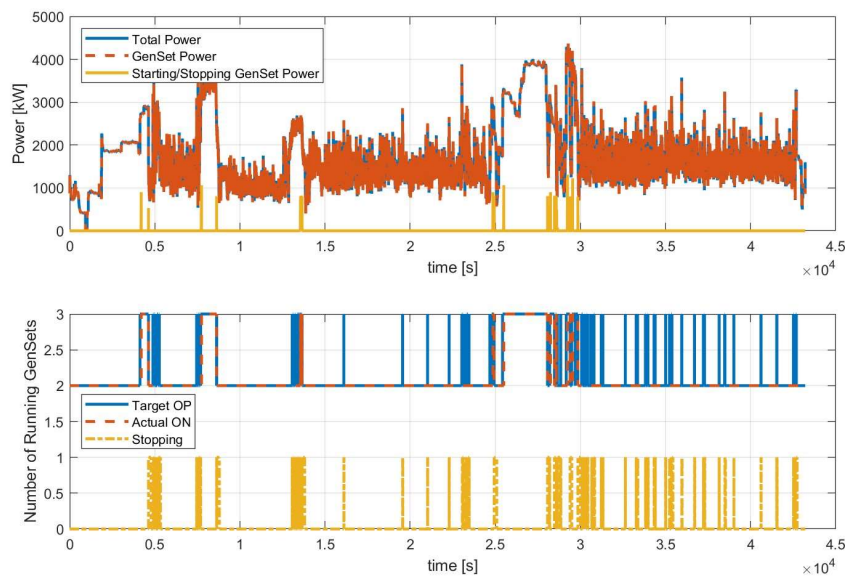


Figure 5-4 OSV-AHC case: Reference operation when no installed ESS.

Figure 5-4 shows the reference operation for DGs without installed ESS. The number of running DGs shown in FIGURE 5-3 is the target number of running DGs for a given load. However, this target number of DGs may not be instantaneously achieved to follow the changes in the load profile. The actual number of running DGs will be different to the target one when a DG is starting/stopping, as shown in Figure 5-4. The operation assumes the state machine presented in FIGURE 5-1b, so a generator in the starting process can be requested to stop and therefore to jump from starting status to stopping status without been full turned-on, and vice versa.

FIGURE 5-5 shows the detailed generator operation profiles for the reference operation when no ESS is installed. It can be noted that at least two DGs are running all the time, as redundance rule applies while in DP2 mode. The DG3 is turned-on sometimes when the load power exceeds the reserve margin threshold long enough to complete the start process or otherwise DG3 jumps from starting state to stopping state following the target number of running DGs.

For the 12-hours operation profile, the DG1 and DG2 present a fuel consumption of around 2.18 tons, while DG3 consumes around 0.35 tons, for a reference total fuel consumption of 4.7 tons for the 12 hours, or around 2063.6 tons per year assuming the same profile during the number of operating days per year (219 days). DG3 is fully turned-on and turned-off 14 times within the 12 hours profile, and 83 times partially starting-stopping (jumping from starting to stopping state without full turned-on, or vice versa).

FIGURE B-11 (appendix B.2) shows the aggregated profiles for the generators for the reference operation. DG1 and DG2 are most of the time loaded between 20% and 40% of their nominal loads, and never loaded more than 87%, while DG3 is around 88.7% of the time turned off and while turned-on is loaded between 30% to 55% of its nominal load and not loaded more than 60%.

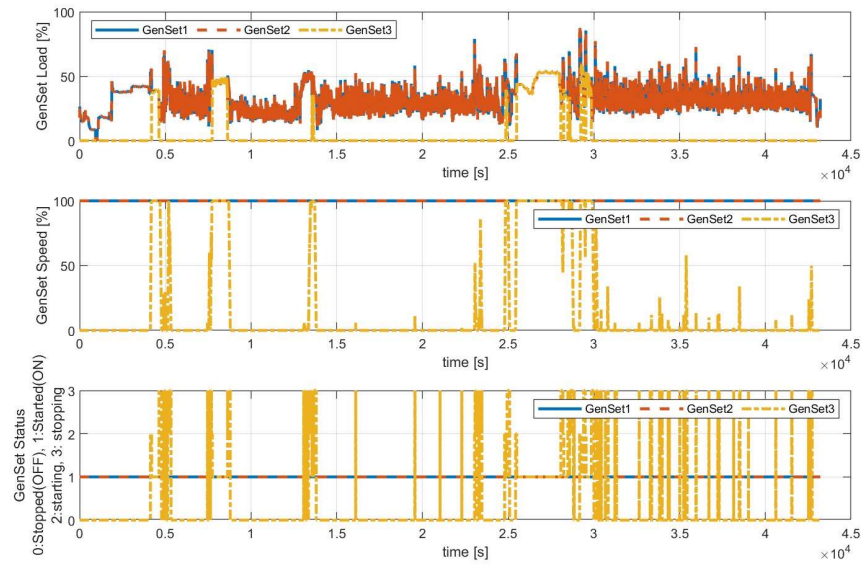


FIGURE 5-5 OSV-AHC CASE: REFERENCE GENERATOR OPERATION PROFILES WHEN NO INSTALLED ESS.

5.3. ESS case studies

5.3.1. ESS only for spinning reserve

When an ESS is installed for spinning reserve, then the operating rule of no DG redundancy with reserve margin, shown in FIGURE 5-3, can be applied. FIGURE 5-6 shows the operation profiles when the ESS is installed only for spinning reserve and 30% DGs reserve margin. For the 12-hours operation profile, the DG1, DG2 and DG3 have a fuel consumption of around 3.45 tons, 0.92 tons and 0.14 tons, respectively, for a total fuel consumption of 4.52 tons for the 12 hours profile, which represents a fuel reduction of about 4.1%. On the other hand, either DG2 or DG3, are in total fully turned-on and turned-off 56 times within the 12 hours profile, and 229 times partially starting-stopping.

FIGURE 5-7 shows the considered ESS profile when ESS is installed only for spinning reserve and 30% DGs reserve margin. The ESS profile is created by assuming the worst-case scenario, so the ESS should take over the load of DG1 when the highest power requirements are needed.

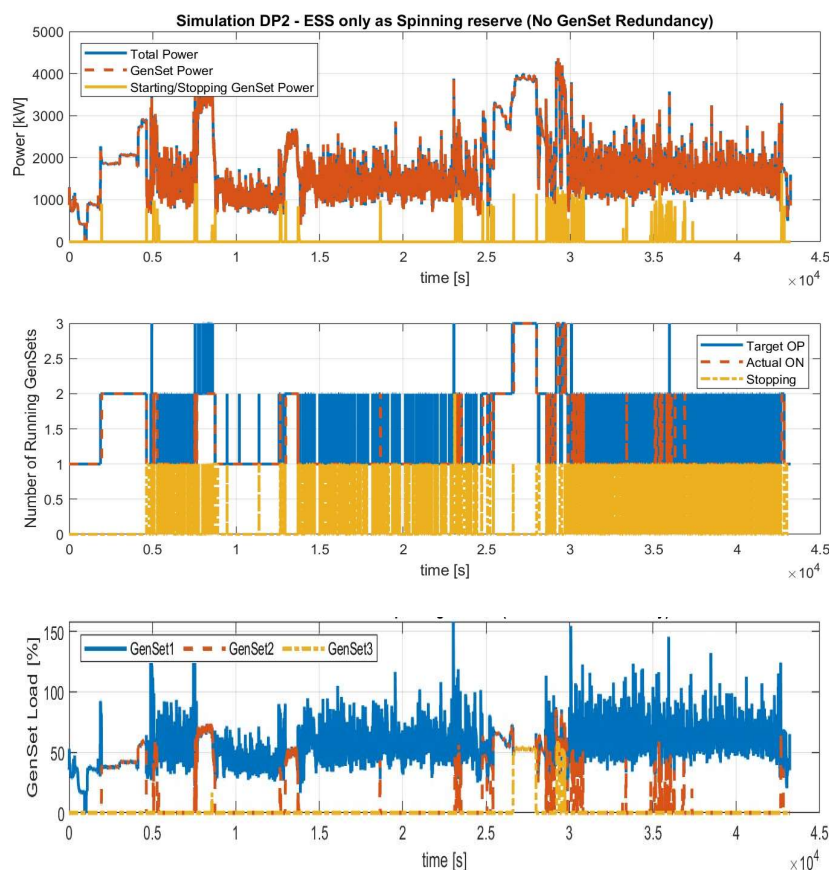


FIGURE 5-6 OSV-AHC CASE: OPERATION PROFILE WHEN ESS IS INSTALLED ONLY FOR SPINNING RESERVE AND 30% DGS RESERVE MARGIN.

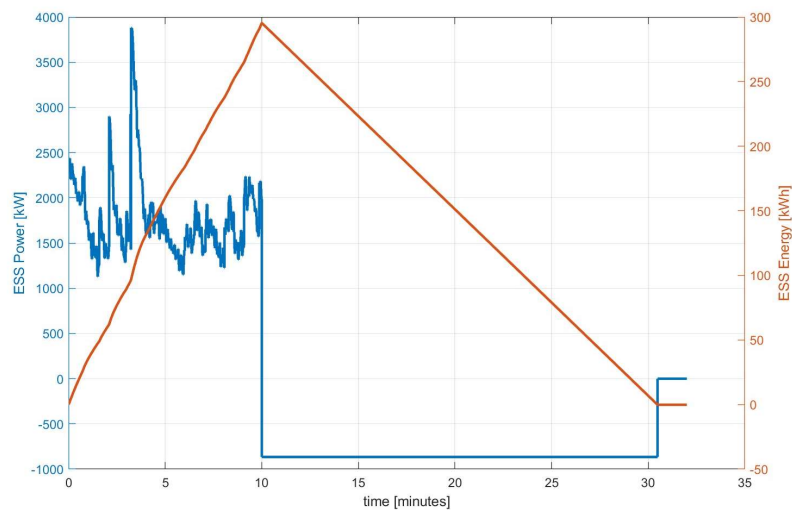


FIGURE 5-7 OSV-AHC CASE: ESS PROFILE WHEN ESS IS INSTALLED ONLY FOR SPINNING RESERVE AND 30% DGS RESERVE MARGIN.

The DG1 power profile is analysed by first extracting a time series of duration equal to the spinning reserve time using the time window with the highest RMS power for DG1. Then, a one-minute series containing the DG1 peak power is added to the previously extracted RMS time window by replacing its peak by the one-minute DG1 peak window. Thus, the highest RMS and peak power are considered for sizing ESS. The charging power is included by considering the maximum charging time after the spinning reserve is used and the amount of energy that need to be charged. For this case the ESS should be sized considering a minimum usable energy of about 300 kWh, while being able to deliver 3881 kW peak, 2259 kW continuous (at least 120s) and 1826 kW in average for 10 minutes.

It can be noted that DG1 is turned-on all the time but DG2 and DG3 only sometimes during the 12-hour profile. In average DG1 is loaded more than reference case, about 55% (most of the time loaded between 40% and 70% of its nominal load). However, DG1 will be also overloaded sometimes because the 30% DG reserve margin is not enough to overcome big changes in the load power, so if possible DG1 could be overloaded up to 57% beyond its nominal power (as observed in FIGURE 5-6) or the AC grid should momentarily overtake this load variation (voltage/frequency oscillation/reduction). In case the overloaded should be limited then an increment in the DG reserve margin should be considered.

FIGURE 5-8 shows the ESS requirements, total fuel consumption and genset overload as function of the DG reserve margin when the ESS is installed only for spinning reserve. It can be noted that as the DG reserve margin decreases, the starting of a new DG is delayed, so DG1 is in average more loaded and exposed to overload events. The ESS requirements become stronger, however the potential for fuel consumption reduction increases, as DGs are in average loaded closer to their optimal operating point when smaller DG reserve margins are used.

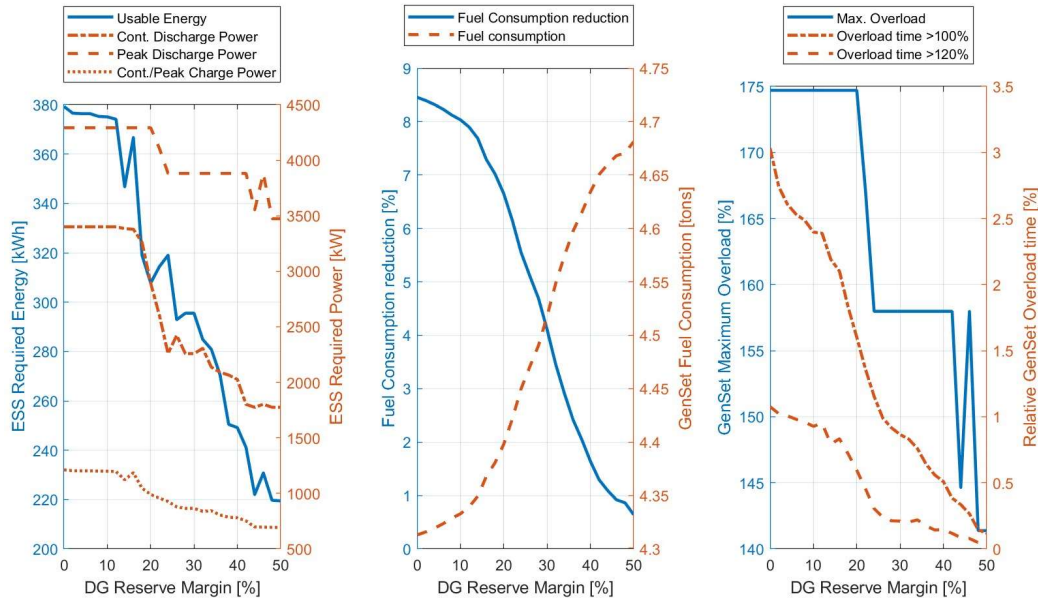


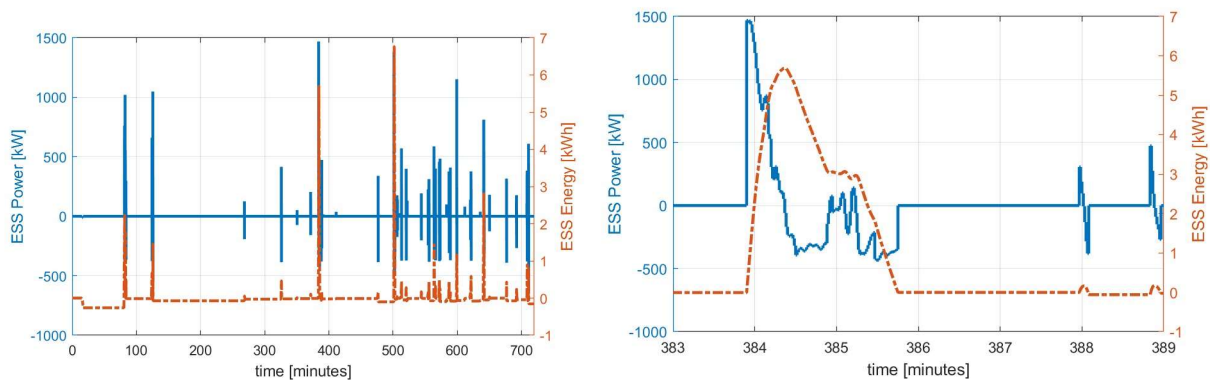
FIGURE 5-8 OSV-AHC CASE: ESS REQUIREMENTS, TOTAL FUEL CONSUMPTION, GENSET OVERLOAD AS FUNCTION OF DG RESERVE MARGIN, WHEN ESS IS INSTALLED ONLY FOR SPINNING RESERVE (SR).

In conclusion, if the ESS is only used for spinning reserve, the DG reserve margin should keep beyond 40% to avoid high overload in the DGs (or consequences in the AC grid), which limits the fuel consumption reduction to less than 1.5%, making this case not attractive. Thus, the ESS should have an additional function, beside spinning reserve, to allow more fuel consumption reduction. However, the ESS should be sized considering the ESS requirements for spinning reserve in addition to the requirements coming from additional ESS functionalities.

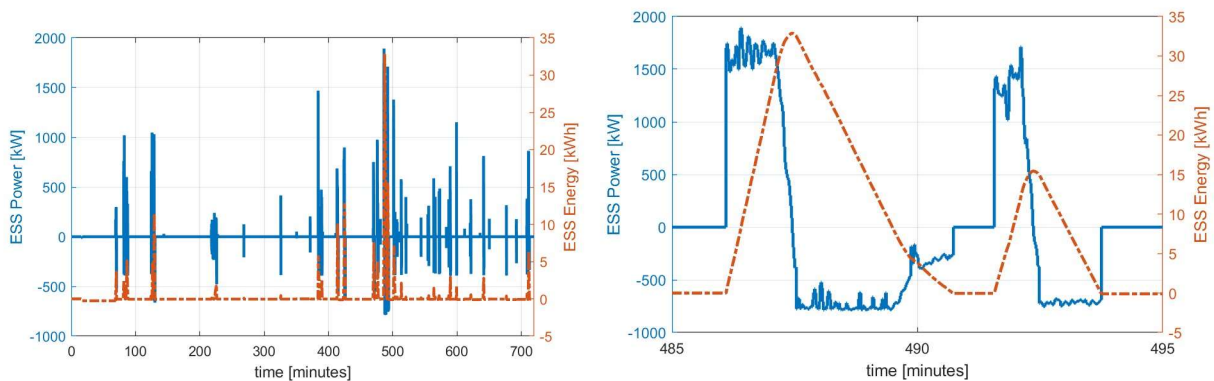
5.3.2. ESS for spinning reserve and peak shaving

Support for avoiding DG overload is considered as an additional functionality in combination to spinning reserve. Small values for the DG reserve margin can be used and therefore increase the potential fuel consumption reduction. Normally, ESS peak shaving functionality is associated to delay in the start of a new DG and to cover the overload by the ESS. As explained before, small DG reserve margins indirectly imply the delay of starting a new DG when the load increases beyond a given value, so to operate the system with small or null DG reserve margin and to use ESS to support DGs is considered as a peak shaving functionality.

FIGURE 5-9 shows two examples of ESS load series for peak shaving (avoid DG overload), when ESS is installed for spinning reserve. FIGURE 5-9a shows the required ESS power and cycled usable energy for the same case shown in FIGURE 5-6 (30% DG reserve margin) while FIGURE 5-9b shows the ESS load series



a) DG reserve margin 30. Left: 12hours series, right: time window when peak discharge power is required.



b) DG reserve margin 0%. Left: 12 hours series, right: time window when peak discharge power is required.

FIGURE 5-9 OSV-AHC CASE: EXAMPLE OF ESS LOAD SERIES WHEN ESS IS INSTALLED FOR SPINNING RESERVE AND PEAK SHAVING WITH NO DG STARTING REQUEST DELAY.

when no DG reserve margin is considered. The ESS discharge power is provided when is needed to avoid loading the DGs beyond its nominal power rating, while ESS is charged by increase maximum 20% the DGs load while the discharged energy is recovered right after a discharge event happens.

FIGURE 5-10 shows the ESS requirements, total fuel consumption and number of DG starts-stops as function of DG reserve margin when ESS is installed for spinning reserve (SR) and peak shaving (PS). By comparing FIGURE 5-10 with the ESS requirements for SR-only in FIGURE 5-8, it can be noted that the ESS power requirements are mainly defined by the SR-profile but not by the PS-profile. However, some increment in the usable energy for PS is needed as well as higher ESS energy throughputs are expected associated with PS as the DG reserve margin decreases.

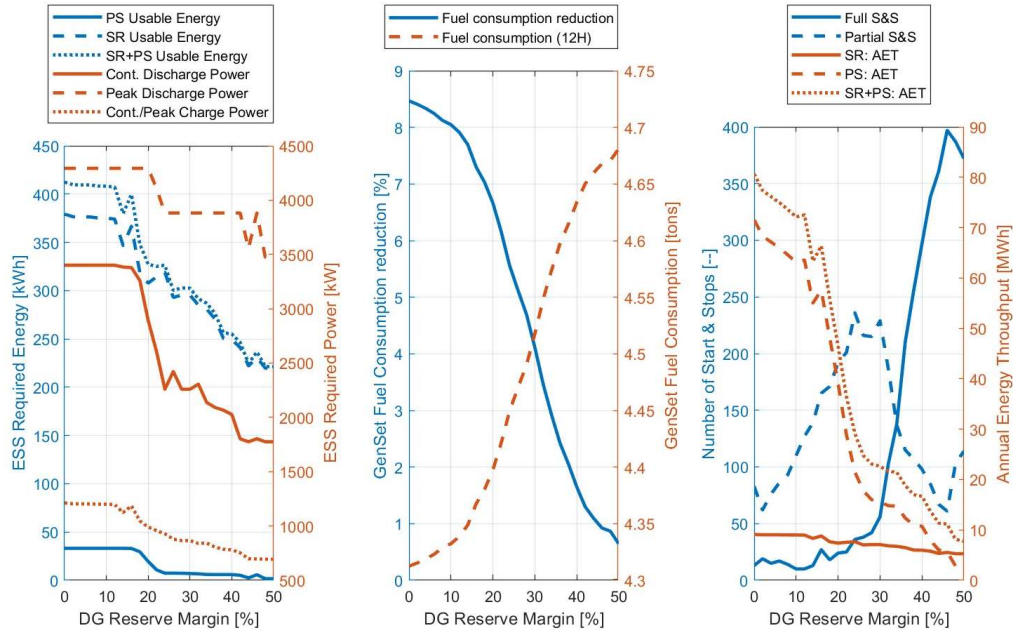
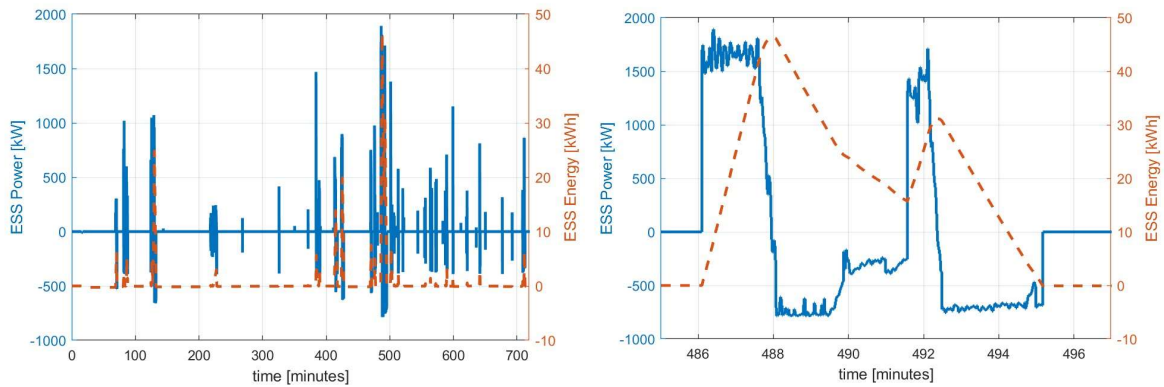
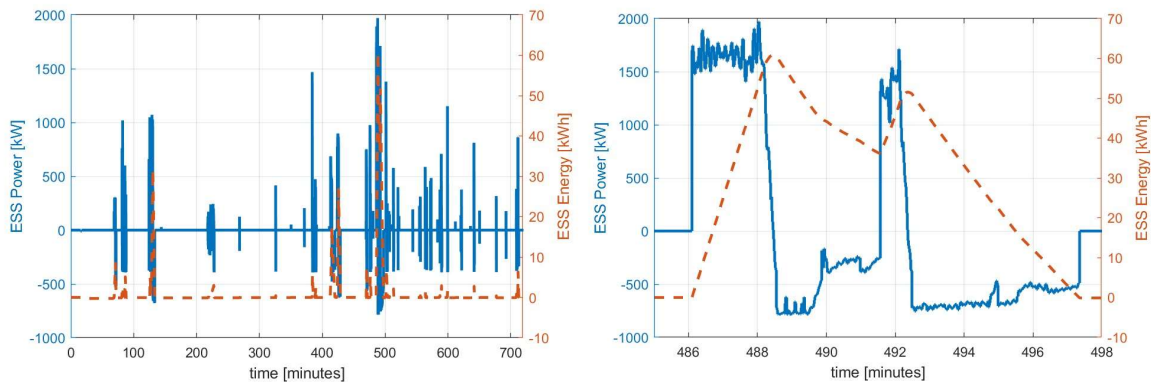


FIGURE 5-10 OSV-AHC CASE: ESS REQUIREMENTS, TOTAL FUEL CONSUMPTION, NUMBER OF DG STARTS-STOPS AS FUNCTION OF DG RESERVE MARGIN, WHEN ESS IS INSTALLED FOR SPINNING RESERVE (SR) AND PEAK SHAVING (PS).

An additional degree of freedom in the PS function can be considered by introducing a DG starting request delay in addition to the DG reserve margin rule. FIGURE 5-11 shows two examples of ESS load series for peak shaving with 0% DG reserve margin 0% but considering a DG starting request delay. FIGURE 5-11a shows the required ESS power and cycled usable energy for 30 s DG starting request delay while FIGURE 5-11b shows the ESS load series when a 60 s DG starting request delay is introduced. As DG starting delay increases the ESS needs more time to discharge and therefore more usable energy will be needed. However, running DGs will be loaded closer to their optimal point, so maybe incrementing the fuel efficiency, besides in some cases starting (or partially starting) a new DG is avoided.



a) DG starting request delay: 30s. Left: 12hours series, right: time window when peak discharge power is required.



b) DG starting request delay: 60 s. Left: 12 hours series, right: time window when peak discharge power is required.

FIGURE 5-11 OSV-AHC CASE: EXAMPLE OF ESS LOAD SERIES WHEN ESS IS INSTALLED FOR SPINNING RESERVE AND PEAK SHAVING AND FOR DG RESERVE MARGIN 0%.

FIGURE 5-12 shows the ESS requirements, total fuel consumption, number of DG starts-stops as function of DG reserve margin and DG start request delay. It can be observed that an additional increment in the fuel consumption reduction can be achieved by introducing the DG start request delay (from 8.45% for 0% reserve margin and 0 start delay, to 9.42% for 0% reserve margin and 720 s start delay). More usable energy is required, and the ESS annual energy throughput and the time ESS is used will increase. However, the ESS power capability requirements do not change as they are linked to the ESS spinning reserve profile. This trade-off is explored for the considered battery technologies to find the optimal BESS solution in section 5.4 and define the study case for HESS sizing.

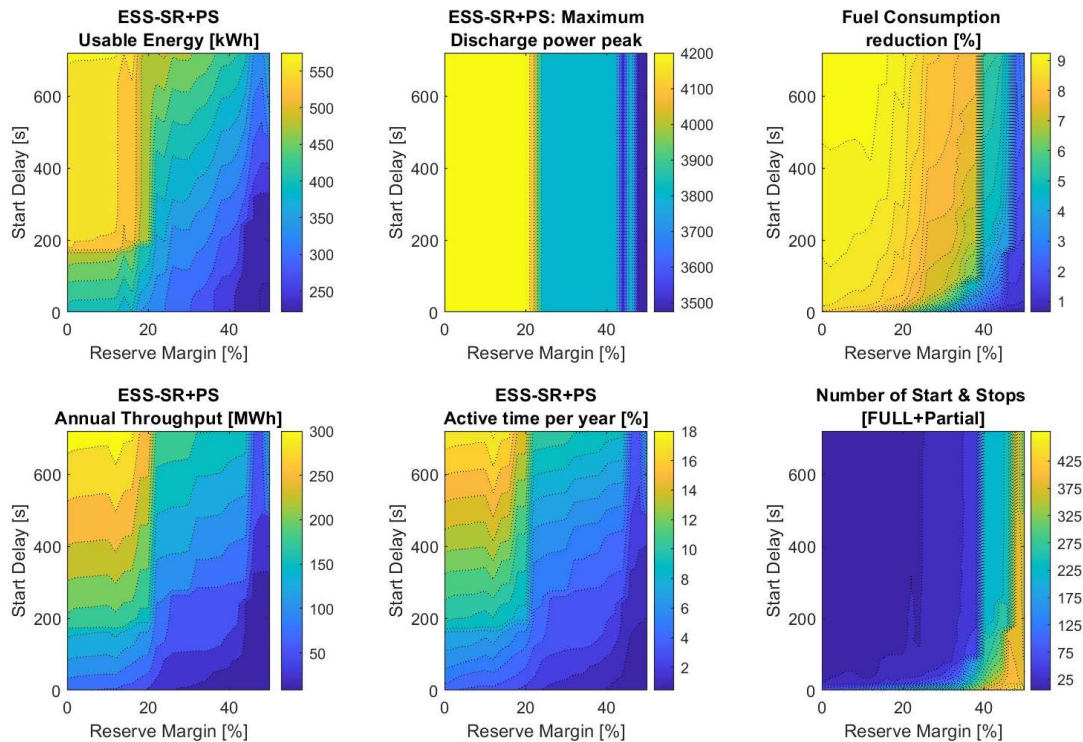


FIGURE 5-12 OSV-AHC CASE: ESS REQUIREMENTS, TOTAL FUEL CONSUMPTION, NUMBER OF DG STARTS-STOPS AS FUNCTION OF DG RESERVE MARGIN AND DG START REQUEST DELAY, WHEN ESS IS INSTALLED FOR SPINNING RESERVE (SR) AND PEAK SHAVING (PS).

5.3.3. ESS for spinning reserve and strategic loading

Another alternative is to use the ESS to minimize fuel consumption by shifting the operation point of the DGs, while providing DG overload support, by using the ESS strategic loading function. To create the operating rules for strategic loading a specific fuel consumption (SFC) margin is considered, so ESS is not discharged if the SFC goes beyond the minimum SFC plus given margin. To illustrate the principle, FIGURE 5-13 shows the strategic loading operating rules for 30% DG reserve margin and 5% SFC margin. For example, if the load power is around 1 MW and the ESS is charged, then the ESS will be in discharge mode. The DGs will be turned-off and the ESS supplies the load power for a while (until reaches a minimum state of charge), then the ESS will be in charge mode, so a DG is turned-on and loaded to an operating point with SFC between minimum SFC (204 g/kWh) and the given threshold ($204 \times 1.05 \approx 214$ g/kWh). The excess power from the DG will be used to charge the ESS.

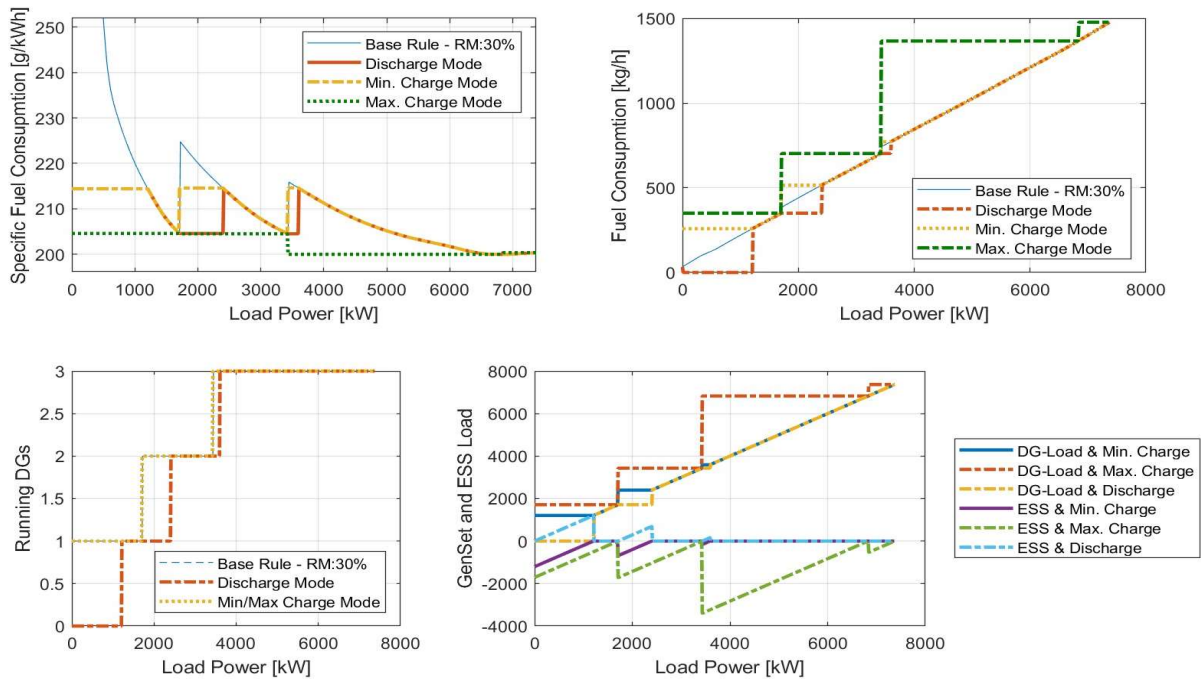


FIGURE 5-13 OSV-AHC CASE: STRATEGIC LOADING OPERATING RULES FOR 30% DG RESERVE MARGIN AND 5% SFC MARGIN.

FIGURE 5-14 shows the ESS requirements, total fuel consumption, number of DG starts-stops as a function of the DG reserve margin and the SFC margin, when the ESS is installed for spinning reserve (SR) and strategic loading (SL). It can be observed that the maximum fuel consumption reduction is lower than for the case with only spinning reserve or spinning reserve in combination with peak shaving case. However, the annual energy throughput and usable energy are lower compared to the peak shaving case, which could be mapped to reduced degradation and therefore reduced sized for the required ESS.

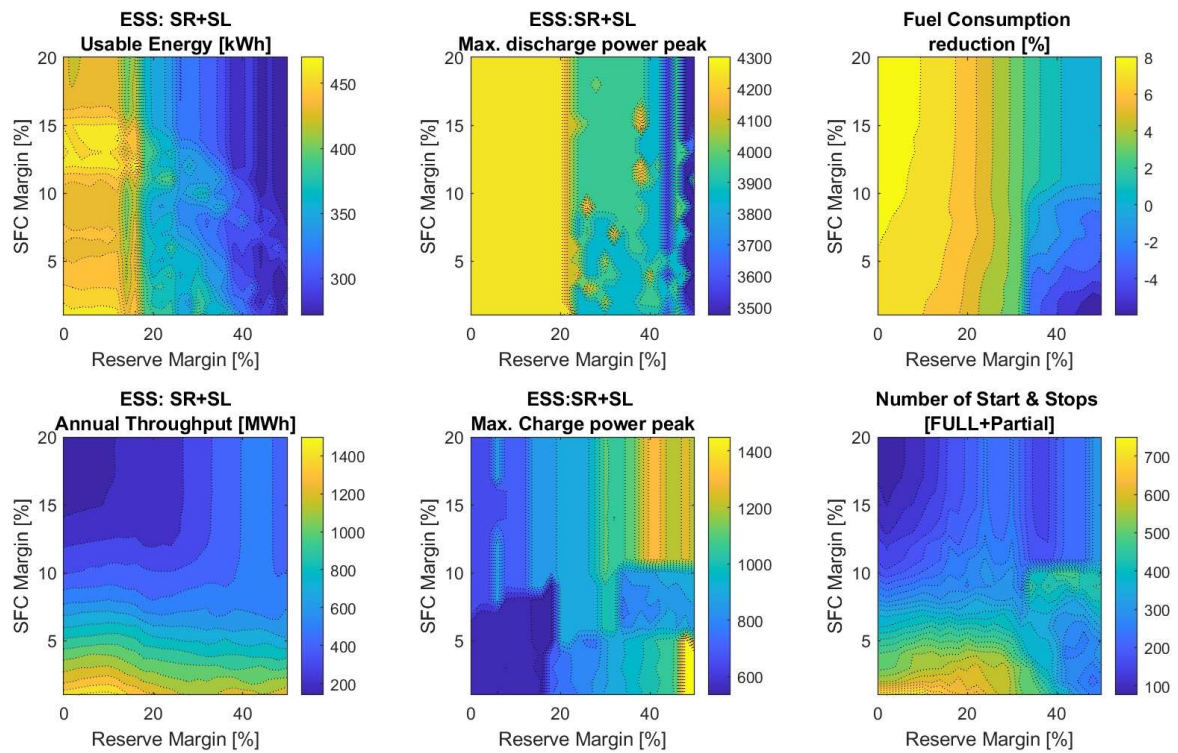


FIGURE 5-14 OSV-AHC CASE: ESS REQUIREMENTS, TOTAL FUEL CONSUMPTION, NUMBER OF DG STARTS-STOPS AS FUNCTION OF DG RESERVE MARGIN AND SFC MARGIN, WHEN ESS IS INSTALLED FOR SPINNING RESERVE (SR) AND STRATEGIC LOADING (SL).

5.4. Optimal BESS solutions

FIGURE 5-15, FIGURE 5-16 and FIGURE 5-17 show the BESS sizing pareto trade-offs between considered performance indices, when ESS is used only as spinning reserve, when the ESS is used for SR and peak shaving (PS) and when the ESS is used for SR and strategic loading (SL), respectively. The OSV+AHC profiles are characterized by high power requirements compared with usable energy needed, so most of the BESS solutions are sized because of power capability requirements. It can be noted that LFP technology brings

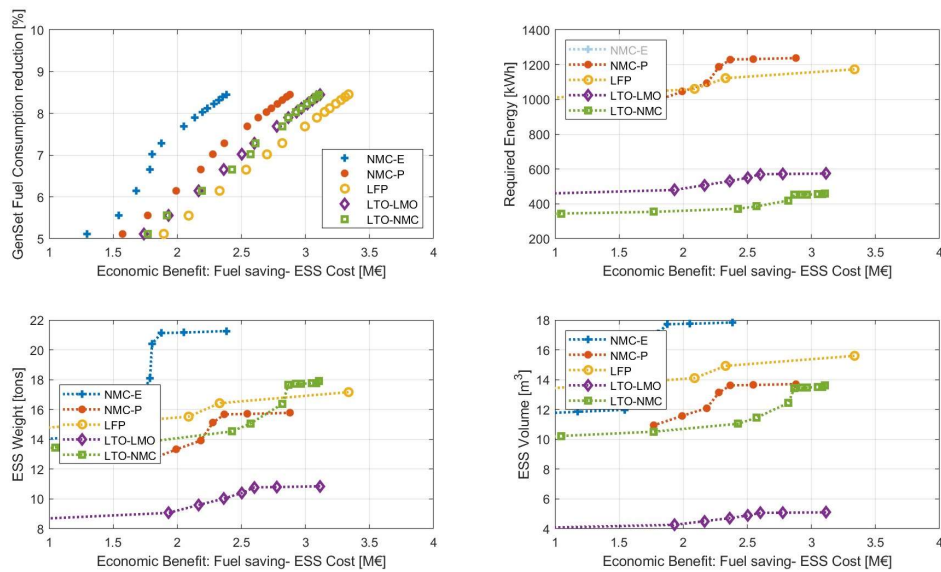


FIGURE 5-15 OSV-AHC CASE: BESS SIZING RESULTS FOR ESS ONLY AS SPINNING RESERVE.

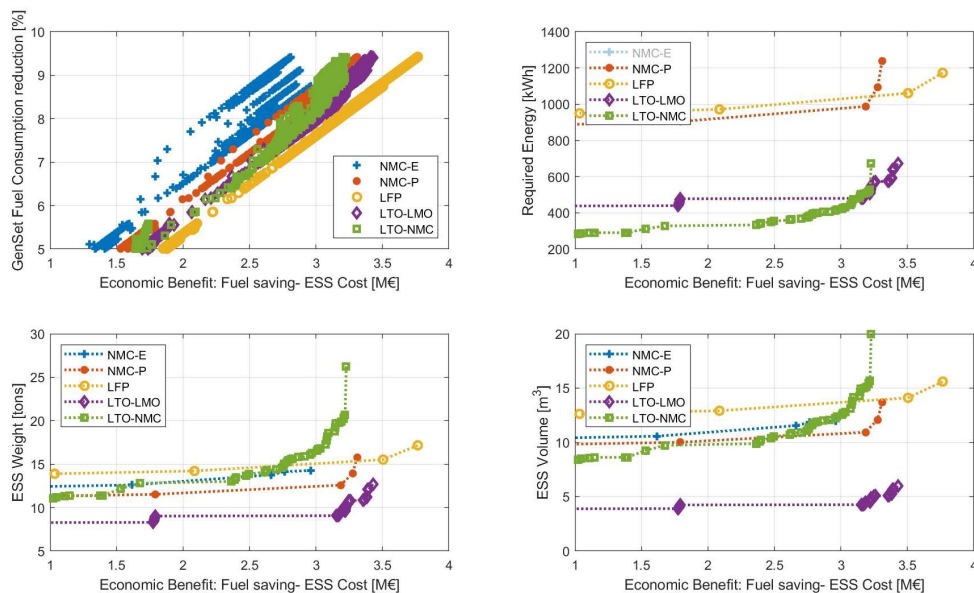


FIGURE 5-16 OSV-AHC CASE: BESS SIZING RESULTS FOR ESS AS SPINNING RESERVE AND PEAK SHAVING.

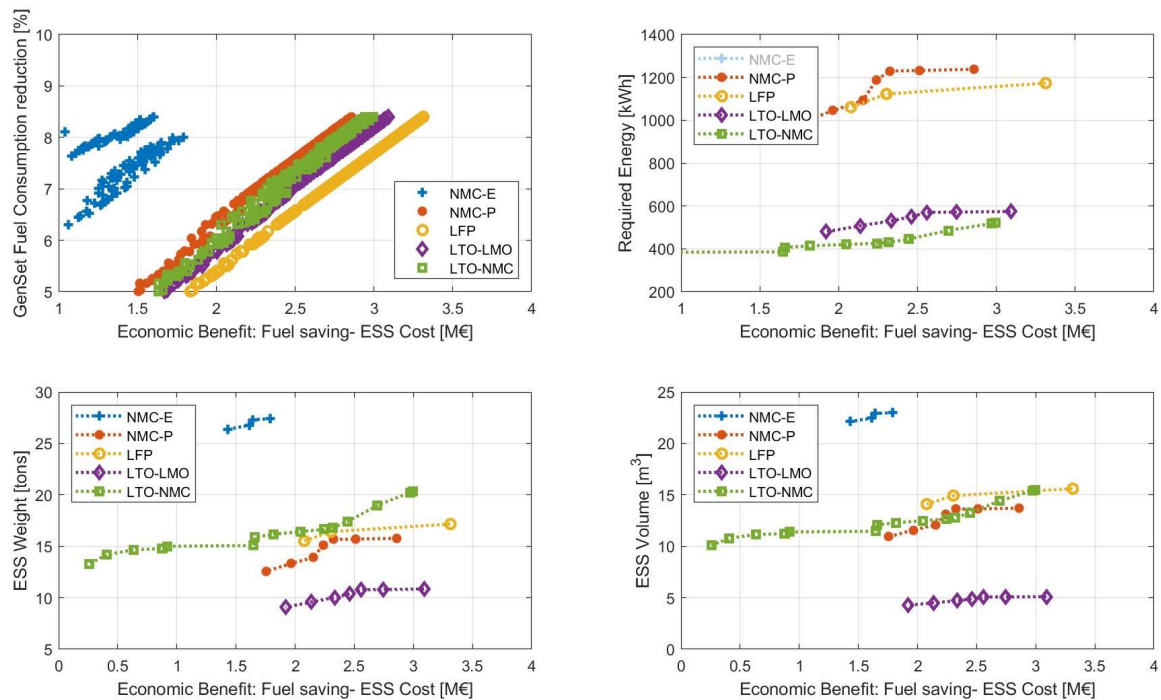


FIGURE 5-17 OSV-AHC CASE: BESS SIZING RESULTS FOR ESS AS SPINNING RESERVE AND STRATEGIC LOADING.

the highest economic benefit for all the cases, while the LTO-LMO shows better trade-off between economic benefits and ESS volume/weight.

Along the three considered ESS cases studies, it can be noted that using the ESS for spinning reserve and peak shaving shows the more convenient use of the ESS, as brings the highest economic benefits with similar BESS capacities.

TABLE 7 summarizes the BESS-only sizing results to maximize the economic benefits for all case studies. The highest economic benefits of 3.766 M€ associated to the highest fuel consumption reduction of 9.423% can be achieved for a 1173kWh BESS solution based on LFP, and when BESS is used for SR and PS with a DG reserve margin of 12% and a DG starting request delay of 720s. This solution is sized because the peak discharge C-rate, showing good potential to be benefit from a HESS solution. On the other hand, the BESS solution based on LTO-LMO technology shows a reduced BESS weight/volume compared to LFP solution, while still showing an economic benefit of 3.429M€. In fact, it can be noted from FIGURE 5-16 that the BESS solutions show a clear trade-off between weight/volume and economic benefits, so at some point, trying to increase the economic benefits will end up in high increments in the BESS size.

TABLE 7 OSV-ACH CASE: BESS-ONLY SIZING RESULTS TO MAXIMIZE ECONOMIC BENEFIT.

Technology	NMC-E	NMC-P	LFP	LTO/LMO	LTO/NMC	
ESS as SR only	Required Energy [kWh]	3409.84	1238.07	1173.33	574.29	458.38
	BESS Cost [k€]	1363.9	866.65	410.66	631.72	641.73
	BESS Volume [m³]	17.837	13.709	15.601	5.104	13.612
	BESS Weight [Tons]	21.263	15.777	17.165	10.851	17.911
	Fuel consumption reduction [%]			8.455		
	Economic Benefit [M€]	2.384	2.881	3.337	3.116	3.106
	ESS Sizing Criteria According to	Cont. DCH C-rate	Cont. DCH C-rate	Peak DCH C-rate	Cont. DCH C-rate	Ensure remaining capacity at EDL
ESS for SR and PS	Required Energy [kWh]	2290.12	1238.07	1173.33	672.17	672.17
	BESS Cost [k€]	916.05	866.65	410.66	739.39	941.04
	BESS Volume [m³]	11.980	13.709	15.601	5.973	19.961
	BESS Weight [Tons]	14.281	15.777	17.165	12.701	26.264
	Fuel consumption reduction [%]	8.745	9.423	9.423	9.405	9.405
	Economic Benefit [M€]	2.960	3.310	3.766	3.429	3.228
	DG reserve margin [%]	24	12	12	12	12
	DG start request delay [s]	720	720	720	640	640
	ESS Sizing Criteria According to	Cont. CH C-rate	Cont. DCH C-rate	Peak DCH C-rate	Calendar aging	Calendar aging
ESS for SR and SL	Required Energy [kWh]	4393.8	1238.07	1173.33	574.29	520.779
	BESS Cost [k€]	1757.5	866.65	410.66	631.72	729.09
	BESS Volume [m³]	22.984	13.709	15.601	5.104	15.465
	BESS Weight [Tons]	27.3986	9.423	17.165	10.851	20.349
	Fuel consumption reduction [%]	8.0032	8.402	8.402	8.402	8.402
	Economic Benefit [M€]	1.790	2.8575	3.314	3.092	2.995
	DG reserve margin [%]	0	0	0	0	0
	SFC margin [%]	6	20	20	20	20
	ESS Sizing Criteria According to	Peak CH C-rate	Cont. DCH C-rate	Peak DCH C-rate	Cont. DCH C-rate	Calendar aging

TABLE 8 OSV-ACH CASE: BESS-ONLY SIZING RESULTS WITH BEST TRADE-OFF BETWEEN ECONOMIC BENEFIT, ESS VOLUME AND ESS WEIGHT.

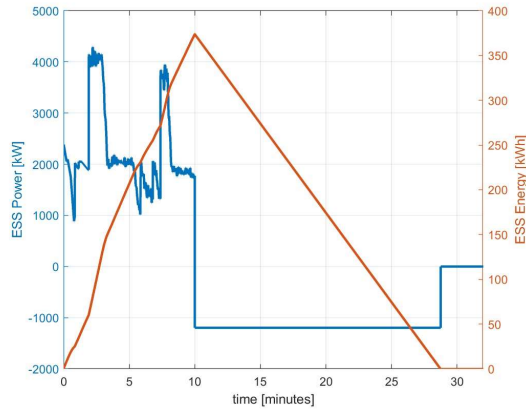
Technology		NMC-E	NMC-P	LFP	LTO/LMO	LTO/NMC
ESS for SR and PS	Required Energy [kWh]	2290.12	987.67	1060.10	480.81	367.72
	BESS Cost [k€]	916.05	691.37	371.35	528.89	514.80
	BESS Volume [m ³]	11.980	10.94	14.107	4.273	10.92
	BESS Weight [Tons]	14.281	12.59	15.52	9.085	14.37
	Fuel consumption reduction [%]	8.745	8.745	8.745	8.335	7.255
	Economic Benefit [M€]	2.960	3.185	3.505	3.165	2.701
	Objective function value:	2	1.633	1.878	1.508	1.257
	DG reserve margin [%]	24	24	24	24	26
	DG start request delay [s]	720	720	720	300	40
	ESS Sizing Criteria According to	Cont. CH C-rate	Peak DCH C-rate	Peak DCH C-rate	Calendar aging	Calendar aging

To choose a BESS solution with better trade-off between economic benefit and volume/weight, the following objective function is considered:

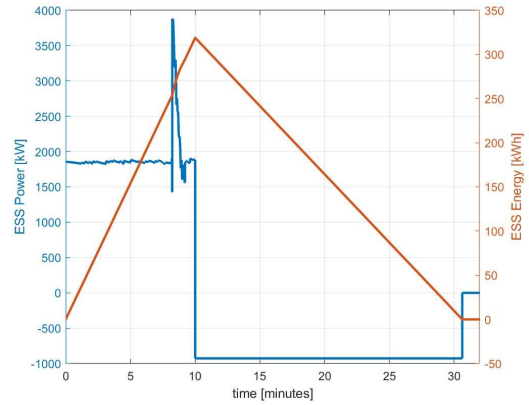
$$OF_{EBVW} = \frac{EB_{MX} - EB}{EB_{MX}} + \frac{ESS_{Volume}}{ESS_{Volume}(EB_{MX})} + \frac{ESS_{Weight}}{ESS_{Weight}(EB_{MX})}$$

where EB is the economic benefit, EB_{MX} is the maximum EB for a given BESS technology, ESS_{Volume} is the ESS volume, $ESS_{Volume}(EB_{MX})$ is the ESS volume for the solution with maximum EB, ESS_{Weight} is the ESS weight and $ESS_{Weight}(EB_{MX})$ is the ESS weight for the solution with maximum EB.

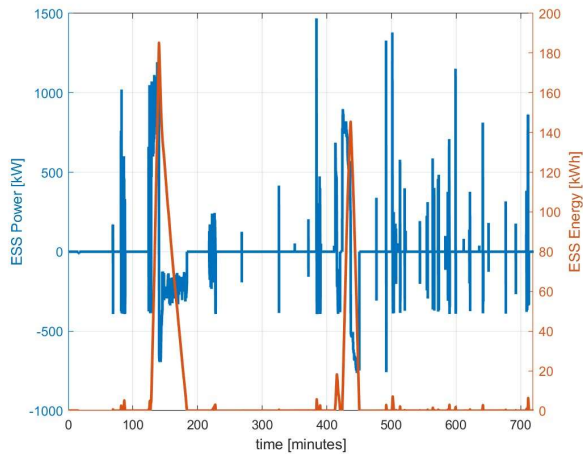
TABLE 8 shows the BESS-only sizing results with best trade-off between economic benefit, ESS volume and ESS weight. LFP and LTO-LMO solutions for use as SR and PS, are taken as reference for HESS analysis in this case as they provide the best trade-offs. FIGURE 5-18 shows the ESS waveform associated with selected solutions.



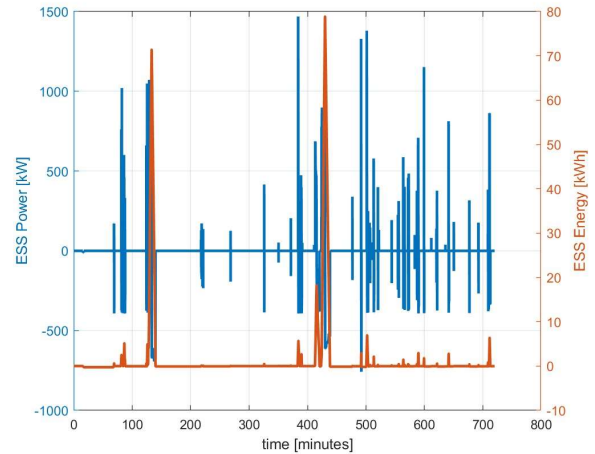
a) ESS spinning reserve profile with DG reserve margin of 12%



b) ESS spinning reserve profile with DG reserve margin of 24%



c) ESS peak shaving profile with DG reserve margin of 24% and DG starting request delay of 720s



d) ESS peak shaving profile with DG reserve margin of 24% and DG starting request delay of 300s

FIGURE 5-18 OSV-AHC CASE: REFERENCE ESS WAVEFORMS. ESS FOR SPINNING RESERVE AND PEAK SHAVING

5.5. HESS solution: Combination of BESS and Supercapacitors

Results for the HESS solutions based on batteries combined with supercapacitors are presented in this section. The combination of SC with all battery technologies/chemistries from [TABLE 3](#) have been checked-out but only the most relevant combinations are reported in this section: LFP batteries with SC, LTO-LMO batteries with SC, and NMC-P batteries with SC, as they have been detected as relevant/optimal BESS solutions from previous section.

First, a combination of LFP batteries with SC is investigated for the case when ESS is used for spinning reserve and peak shaving, while considering a DG reserve margin of 24% and a DG starting request delay of 720 s as optimal operating parameters found to provide the best trade-off between economic benefits and LFP-BESS volume/weight following results in [TABLE 8](#). For this case, the HESS is designed to fulfil power profiles for spinning reserve and peak shaving, shown in [FIGURE 5-18b](#) and [FIGURE 5-18c](#), respectively, so the optimal HESS-EMS parameters have been found for each profile.

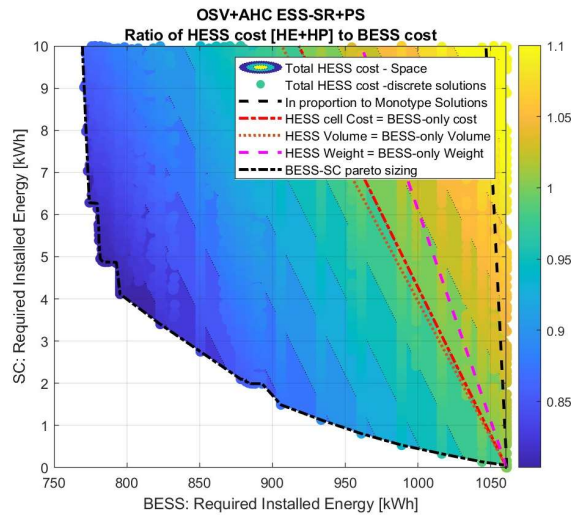
For the combination of LFP batteries with SC, also a solution for maximum economic benefit is explored, which is the case when ESS is used for spinning reserve and peak shaving, while considering a DG reserve margin of 12% and a DG starting request delay of 720 s following results in [TABLE 7](#).

[FIGURE 5-19](#) reports the main HESS sizing results for combination of Li-ion LFP batteries and supercapacitors, when the HESS is used for SR and PS functionalities with a DG starting request delay of 720 s and for two DG reserve margins, 12% and 24%, which corresponds to the LFP-BESS-only solutions with the highest economic benefit and the best Cost-Volume-Weight trade-offs, as reported in [TABLE 7](#) and [TABLE 8](#), respectively.

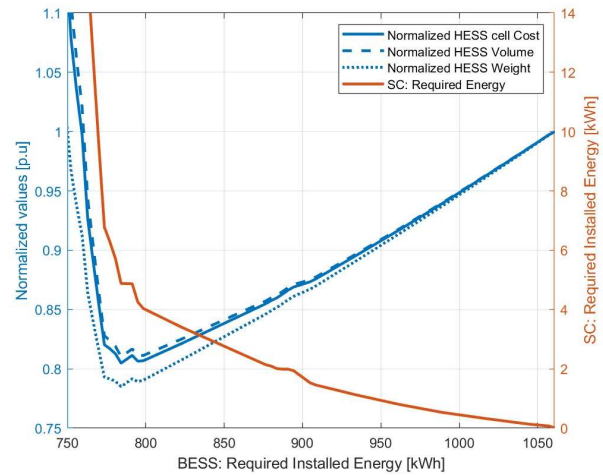
For the solution with best trade-offs ([FIGURE 5-19a](#) and [FIGURE 5-19b](#)), it can be observed that the combination of LFP batteries with SC brings benefits for this power profile as HESS cost, volume and weight decrease as the SC installed capacity increases until around 4-5 kWh, which allows for a reduction in the LFP-BESS energy from 1061 kWh to around 780-800 kWh, and a reduction in the ESS cost, volume and weight of around 80% compared with LFP BESS-only solution. By including the SC in this case, the peak discharge requirement, which is the sizing limiting factor for LFP battery in this case (see [TABLE 8](#)), can be reduced and, therefore, a reduction of LFP battery can be achieved.

For the solution associated with the highest economic benefits, [FIGURE 5-19c](#) and [FIGURE 5-19d](#), a different trend is observed, showing optimal cost, volume and weight at different LFP-SC combinations. Introducing SC allows for a maximum reduction of about 5% in cost and volume compared with the LFP-BESS-only solution when installing around 0.5 kWh SC. Beyond 0.5 kWh a further reduction can be obtained for weight but not for volume or cost. The maximum weight reduction of about 6% can be achieved by installing around 6 kWh SC.

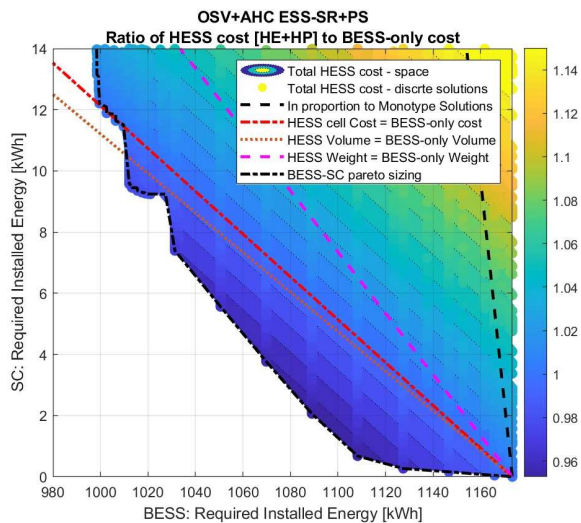
The second HESS case considered in this subsection is the combination of LTO-LMO batteries with SC when the ESS is used for spinning reserve and peak shaving, while considering a DG reserve margin of 24% and a DG starting request delay of 300 s as optimal operating parameters found to provide the best trade-off between economic benefits and LTO-LMO-BESS volume/weight according to [TABLE 8](#). For this case, the



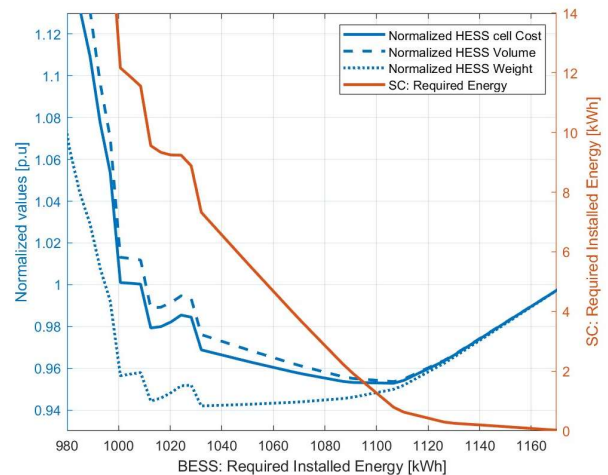
a) Required Energy performance space (zoom for SC installed energy <10kWh). Best trade-off solution. DG reserve margin: 24%



b) Required SC energy, HESS cost, volume and weight pareto optimalities versus required BESS installed energy. Best trade-off solution. DG reserve margin: 24%



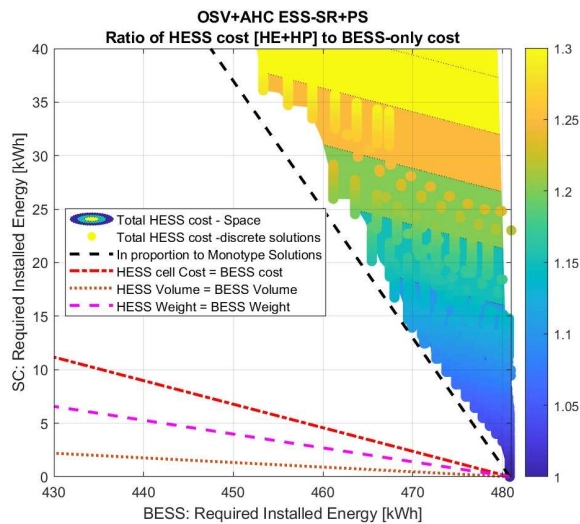
c) Required Energy performance space (zoom for SC installed energy <14kWh). Highest Economic benefit solution. DG reserve margin: 12%



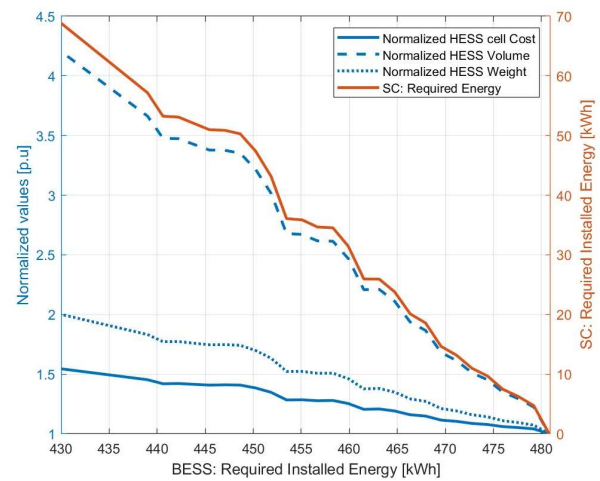
d) Required SC energy, HESS cost, volume and weight pareto optimalities versus required BESS installed energy. Highest Economic benefit solution. DG reserve margin: 12%

FIGURE 5-19 OSV-AHC CASE (ESS AS SR AND PS): HESS SIZING RESULTS FOR COMBINATION OF LI-ION LFP BATTERIES AND SUPERCAPACITORS. DG STARTING REQUEST DELAY 720S.

HESS is designed to fulfil power profiles for spinning reserve and peak shaving, shown in FIGURE 5-18b and FIGURE 5-18d, respectively, so the optimal HESS-EMS parameters have been found for each profile.



a) Required Energy performance space (zoom for SC installed energy <40kWh)



b) Required SC energy, HESS cost, volume and weight pareto optimalities versus required BESS installed energy

FIGURE 5-20 OSV-AHC CASE (ESS AS SR AND PS): HESS SIZING RESULTS FOR COMBINATION OF LI-ION LTO-LMO BATTERIES AND SUPERCAPACITORS. DG RESERVE MARGIN: 24% AND DG STARTING REQUEST DELAY 300S.

FIGURE 5-20 shows the main HESS sizing results for a combination of Li-ion LTO-LMO batteries and supercapacitors, when the HESS is used for SR and PS functionalities with DG reserve margin of 24% and a DG starting request delay of 300 s. It can be noted that for the analysed power profile, the combination of LTO-LMO batteries with supercapacitors does not bring advantages over BESS-only solution based on LTO-LMO batteries. The main reason for these results is that the sizing limiting rule for LTO-LMO-BESS-only solution is the calendar aging, as reported in TABLE 8, so the high-power capability of supercapacitors is not fully used in this case.

Looking at TABLE 8, NMC-P batteries also have as limiting sizing factor the peak discharge power, so they have been considered as third HESS case. FIGURE 5-21 shows the main HESS sizing results for a combination of Li-ion NMC-P batteries and supercapacitors, when the ESS is used for spinning reserve and peak shaving, while considering a DG reserve margin of 24% and a DG starting request delay of 720 s as optimal operating parameters. It can be observed that the combination of NMC-P batteries with SC also brings benefits for this power profile. The HESS solutions for this case show different trade-off compared with the LFP case, having an optimal solution for each performance index (cost, volume, weight). All performance indices reduce as the SC size increases from 0 to around 2 kWh, then for SC size between 2 kWh and around 14 kWh, the HESS volume increases, while HESS weight finds a minimum and start increasing while the HESS cost continues to reduce. For a SC size beyond 14 kWh, all performance indices increase abruptly.

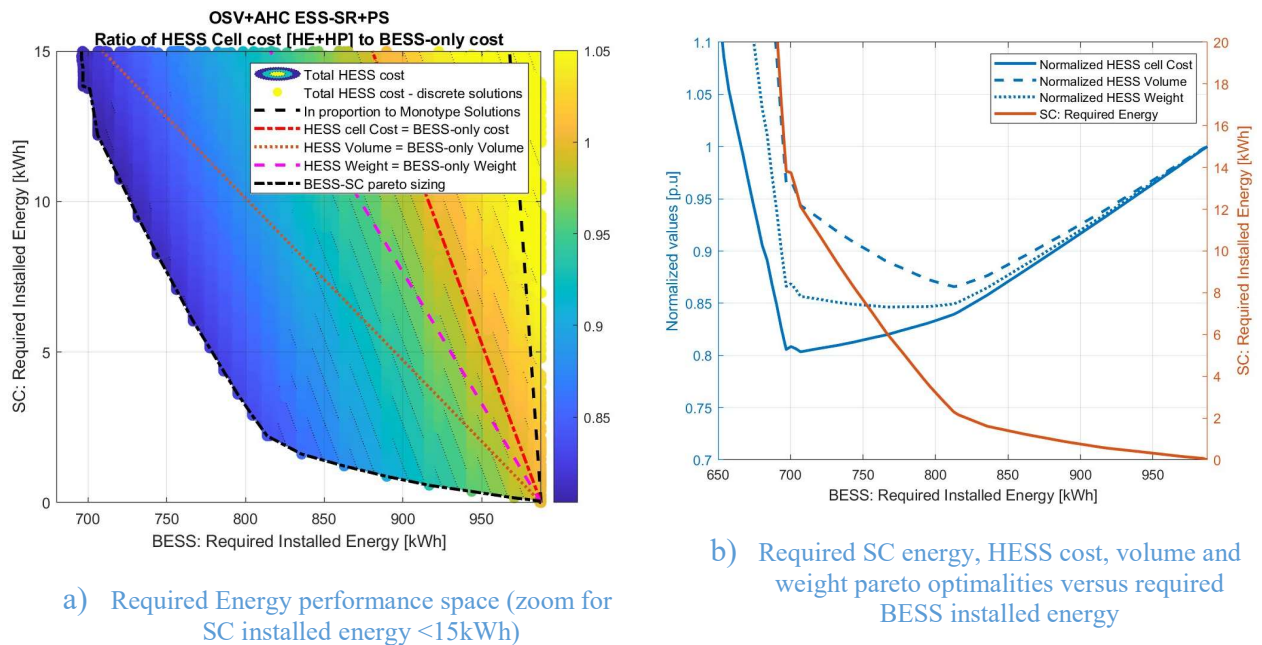
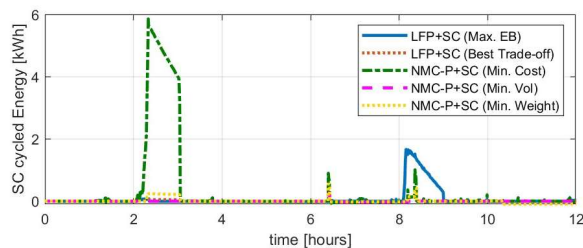
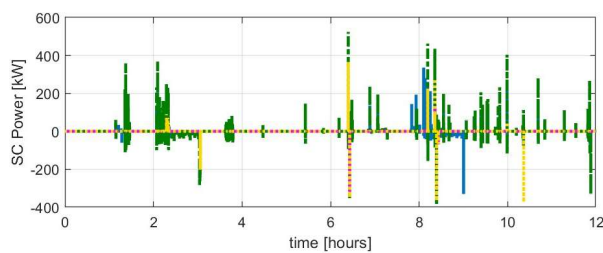


FIGURE 5-21 OSV-AHC CASE (ESS AS SR AND PS): HESS SIZING RESULTS FOR COMBINATION OF LI-ION NMC-P BATTERIES AND SUPERCAPACITORS. DG RESERVE MARGIN: 24% AND DG STARTING REQUEST DELAY 720S.

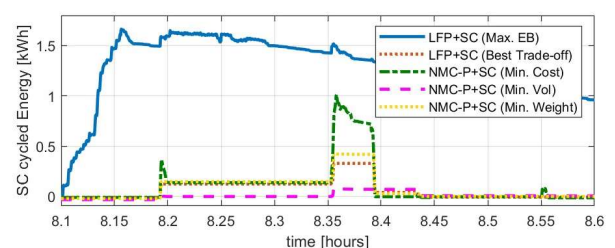
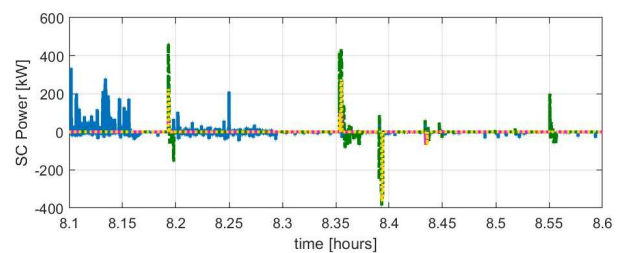
TABLE 9 summarizes the best HESS solutions when the BESS is combined with a SC. While, FIGURE 5-22 shows the SC waveforms of the HESS selected solutions for combination of Li-ion batteries and supercapacitors, for the OSV+AHC fundamental cycle (FIGURE 5-22a) and a zoom when SC peak energy is reached (FIGURE 5-22b).

TABLE 9 OSV-AHC CASE (ESS AS SR AND PS): HESS SIZING RESULTS FOR BESS COMBINED WITH SC.

Solution Target		Ref. BESS-Only		HESS Best trade-off				HESS Max. EB	
BESS Tech		LFP	LTO-LMO	LFP	NMC-P			LFP	
Required Energy [kWh]	BESS	1060.1	480.81	781.7	706.24	813.74	766.77	1089.0	
	SC	--	--	4.955	12.20	2.213	6.024	2.060	
HESS Cost [k€]		371.35	528.89	298.38	555.37	580.68	566.86	391.44	
HESS Volume [m³]		14.107	4.273	11.412	10.33	9.465	9.728	14.90	
HESS Weight [Tons]		15.52	9.085	12.160	10.78	10.69	10.65	16.23	
Fuel consumption reduction [%]		8.745	8.335	8.745				9.423	
Economic Benefit [M€]		3.505	3.165	3.578	3.321	3.296	3.310	3.785	
DG reserve margin [%]		24							12
DG start request delay [s]		720	300	720					



a) Fundamental OSV+AHC profile cycle

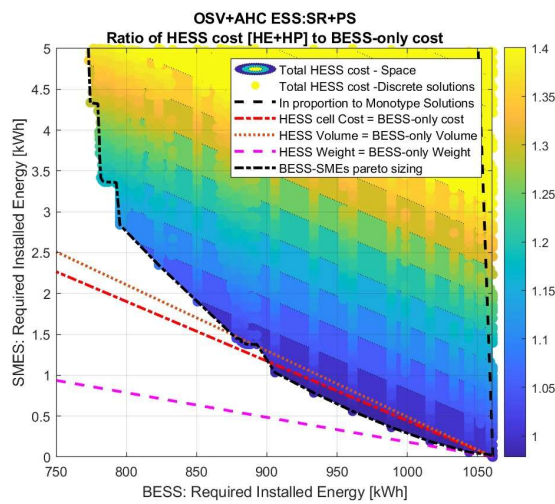


b) Zoom when SC peak energy is reached for max. EB solution.

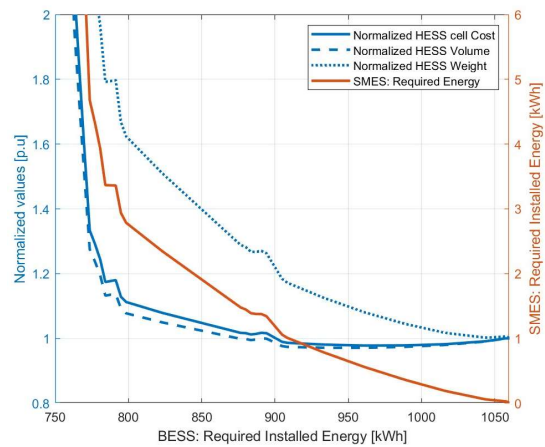
FIGURE 5-22 OSV-AHC CASE (ESS AS SR AND PS): SC WAVEFORMS OF THE HESS SELECTED SOLUTIONS FOR COMBINATION OF LI-ION BATTERIES AND SUPERCAPACITORS FOR PEAK SHAVING.

5.6. HESS solution: Combination of BESS and SMES

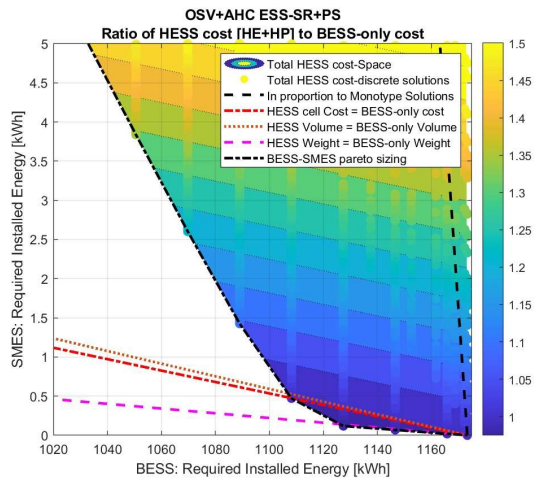
Similar procedure as for the previous case was followed for the HESS solution combining BESS with SMES. However, for the case of SMES, the HESS cost is evaluated against the ship lifetime (30 years), instead of the ESS design life (10 years), as the SMES degradation is negligible. Thus, the total cost of the HESS solution will include the BESS replacements to the ship lifetime (3 replacements), and therefore the reference cost of BESS-only solution will be three times the reported cost in TABLE 8.



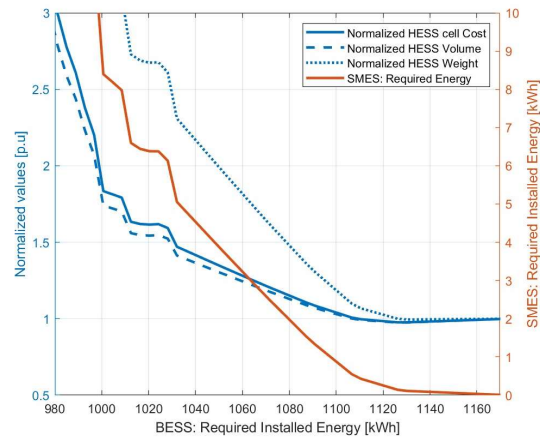
a) Required Energy performance space (zoom for SMES installed energy <5kWh). Best trade-off solution. DG reserve margin: 24%



b) Required SMES energy, HESS cost, volume and weight pareto optimalities versus required BESS installed energy. Best trade-off solution. DG reserve margin: 24%



c) Required Energy performance space (for SMES installed energy <5kWh). Highest Economic benefit solution. DG reserve margin: 12%



d) Required SMES energy, HESS cost, volume and weight pareto optimalities versus required BESS installed energy. Highest Economic benefit solution. DG reserve margin: 12%

FIGURE 5-23 OSV-AHC CASE (ESS AS SR AND PS): HESS SIZING RESULTS FOR COMBINATION OF LI-ION LFP BATTERIES AND SMES. DG STARTING REQUEST DELAY 720S.

FIGURE 5-23 shows the main HESS sizing results for combination of Li-ion LFP batteries and SMES, when the HESS is used for SR and PS functionalities with a DG starting request delay of 720 s and for two DG reserve margins, 24% (FIGURE 5-23a-b) and 12% (FIGURE 5-23c-d), which corresponds to the LFP-BESS-only solutions with the highest economic benefit and the best Cost-Volume-Weight trade-offs, as reported in TABLE 7 and TABLE 8, respectively.

For the LFP solution with best trade-off (FIGURE 5-23a-b), it can be noted that for small size SMESs the LFP-BESS capacity can be reduced while keeping similar volume and total cost as for LFP BESS-only solution but with some increment in the total weight. By installing a 1 kWh SMES, the LFP BESS capacity can be reduced about 160 kWh, from 1060 kWh to around 900 kWh, while keeping similar volume and cost but with an increment in the total weight of about 20%, compared with a LFP BESS-only solution.

For the LFP solution with the highest economic benefit (FIGURE 5-23c-d), it is possible to find HESS solutions that reduce the volume and cost while keeping similar total weight, but there are limited to a small range of SMES capacities and BESS energy capacities reductions. By reducing the LFP-BESS energy by more than 30 kWh (below 1130kWh), the required SMES energy increases rapidly, and the performance of HESS solutions decreases.

FIGURE 5-24 shows the main HESS sizing results for a combination of Li-ion NMC-P batteries and SMES, when the ESS is used for spinning reserve and peak shaving, while considering a DG reserve margin of 24%

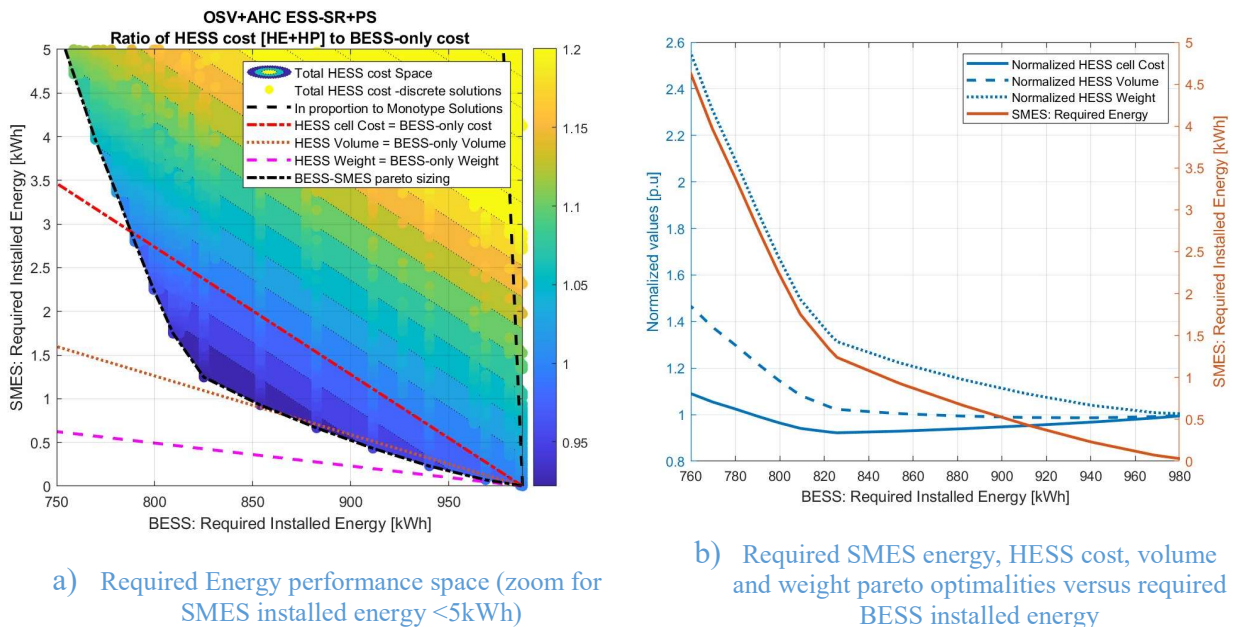


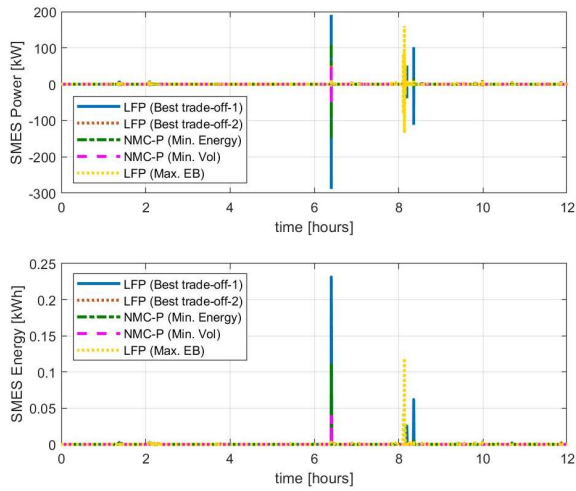
FIGURE 5-24 OSV-AHC CASE (ESS AS SR AND PS): HESS SIZING RESULTS FOR COMBINATION OF LI-ION NMC-P BATTERIES AND SMES. DG RESERVE MARGIN: 24% AND DG STARTING REQUEST DELAY 720S.

TABLE 10 OSV-AHC CASE (ESS AS SR+PS): HESS SIZING RESULTS FOR BESS COMBINED WITH SMES.

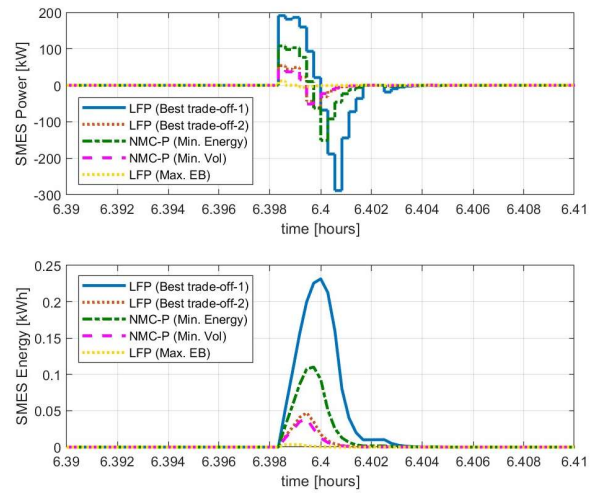
Solution Target		Ref. BESS-Only		HESS Best trade-off				HESS Max. EB
BESS Tech		LFP	LTO-LMO	LFP		NMC-P		LFP
Required Energy [kWh]	BESS	1060.1	480.81	961.1	1016.4	825.08	940.06	1127.4
	SMES	--	--	0.5599	0.1898	1.246	0.2295	0.1187
HESS Cost (30 years) [M€]		1.1141	1.5867	1.0898	1.0945	1.9122	2.0072	1.2009
HESS Volume [m ³]		14.107	4.273	13.701	13.826	11.189	10.787	15.186
HESS Weight [Tons]		15.52	9.085	16.778	15.790	16.565	13.094	17.070
Fuel consumption reduction [%]		8.745	8.335	8.745				9.423
Economic Benefit [M€]		10.515	9.495	10.540	10.535	9.717	9.622	11.329
DG reserve margin [%]		24						12
DG start request delay [s]		720	300	720				

and a DG starting request delay of 720 s as optimal operating parameters. For this case, the HESS cost can be reduced up to 90% of the NMC-P BESS-only solution while keeping similar volume but having an increment of about 30% in the total weight compared to an NMC-P BESS-only solution. The combination of NMC-P and SMES brings better margins compared to the combination of LFP and SMES, however the weight is a limiting factor for the SMES.

TABLE 10 summarizes the best HESS solutions for BESS combined with SMES. It can be noted that the best HESS solutions cannot reduce the volume/weight of the BESS-only solution based on LTO-LMO, however HESS solutions can bring a reduction on HESS cost and therefore increment in the ship-lifetime economic benefit. The combination of SMES with LFP batteries can bring solutions with lower HESS cost and higher economic benefit but more volume and weight compared with the combination of SMES with NMC-P batteries. **FIGURE 5-25** shows the SMES waveforms of the HESS selected solutions for combination of Li-ion Batteries and SMES, for the OSV+AHC peak-shaving fundamental cycle (**FIGURE 5-25 a**) and a zoom when SC peak energy is reached for most the solutions (**FIGURE 5-25b**).



a) Fundamental OSV+AHC peak-shaving profile cycle



b) Zoom when SMES peak energy is reached for most of the solutions.

FIGURE 5-25 OSV-AHC CASE (ESS AS SR AND PS): SMES WAVEFORMS OF THE HESS SELECTED SOLUTIONS FOR COMBINATION OF BATTERIES WITH SMES.

6. Stern Trawler

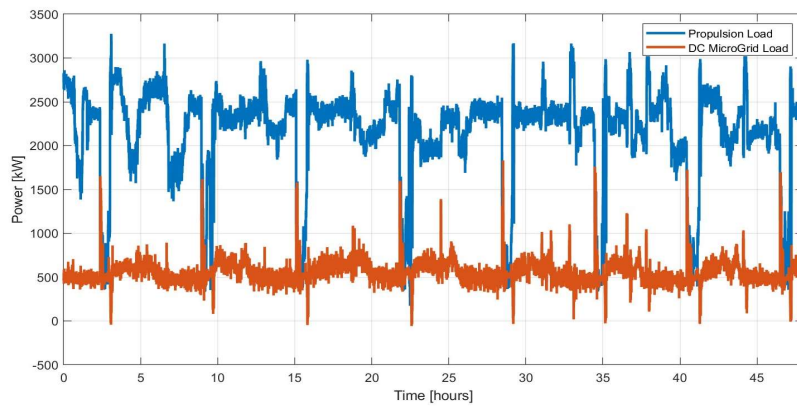
6.1. Mission Profile and General Specifications

A stern trawler is a vessel mainly used for fishing and its typical operating cycles include high power peaks during shooting and heave of the trawl. This case follows the stern trawler case definition in [17], which considered a vessel with a rule length of 73.23 m. The SDL diagram for Trawler case is presented in FIGURE A-3 (Appendix A.2). The trawler power system can be divided into three subsystems:

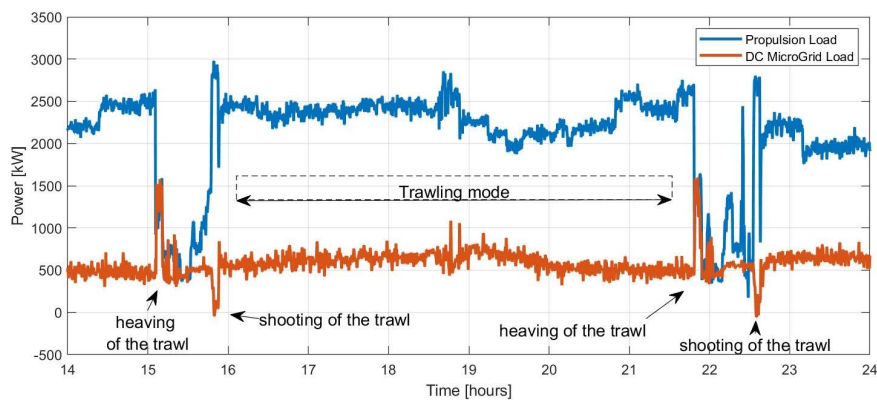
- **The main mechanical propulsion shaft** interconnects mechanically the main engine and the main propulsion through a main reduction gear. It also includes a shaft generator (PTI/PTO unit) connected to the main reduction gear, which enables transfer power from the main engine to the DC microgrid and vice versa. The shaft generator is interfaced to the DC microgrid by x2 variable frequency AC/DC converters.
- **The main switchboard** is a 440V/60Hz AC grid, which includes the general consumer loads, a shore connection cabinet and an auxiliary generator unit. It is interconnected to the DC microgrid through two transformers and AC/DC converter units.
- **A DC microgrid** that interconnects the shaft generator (PTI/PTO unit), the winch switchboard, the tunnel thruster, and the main switchboard. The ESS is connected to the DC microgrid through a DC/DC converter.

The profile power time series is based on the following assumptions:

- Trawler power demand is based on log data provided by Vard Electric, which includes the main vessel operation: during trawling mode, when shooting trawl and when heaving trawl. The reference stern trawler log data is presented in appendix A.4, FIGURE A-9. The original log data length is 48 hours with a sample rate of 15 seconds.
 - The log data does not include power transferred between the AC grid and the DC microgrid, so it is assumed no power from/to the AC grid for the log data profile.
 - A sample rate of 5 second is considered for the trawler load demand, so the reference log data has been resampled using a cubic interpolation method.
- The trawler load profile is composed by two components:
 - Propulsion power
 - DC microgrid load: compressing the thruster load and the winch load.
 - DC microgrid load has been estimated from the log data as the difference between PTO generated power and the ESS discharged power, as no power from/to AC grid was found in the log data.
- Assumed profile operation:
 - Operating days per year: 240 days (around 65% operating time per year).
 - No seasonal/geographical variations to the load profile



a) 48 Hours mission profile



b) Zoom to the basic trawling operation.

FIGURE 6-1 TRAWLER STANDARD MISSION PROFILE.

The trawler load profile is shown in FIGURE 6-1. It can be noted that the DC microgrid load profile has some power peaks when shooting and heaving the trawl, which happens at the same time of a reduction and increment in the propulsion load, respectively.

The main/relevant components specifications considered in this case study are as follows:

- Main propulsion: 5700kW / approx. 40-136rpm
- Main Engine: Diesel engine with rated power of 4800kW, and speed 500-750rpm. This diesel engine follows a scaled version of the SFC curve provided by Vard Electric, reported in Figure A 7, appendix A.4.
- PTI/PTO unit:
 - PTI rated power: 1500kW.
 - Average electric to mechanical power efficiency: 90%
 - PTO rated power: 2500kW.
 - PTI/PTO maximum power up/down ramp: 28 kW/s
 - Average mechanical to electric power efficiency: 92%

- Auxiliar Generator: 440V/60Hz diesel generator with rated power of 1700kW/1888kVA.
- Average conversion efficiency from AC grid to DC microgrid: 94%
- Average conversion efficiency from PTO unit to DC microgrid: 96%
- Reference ESS: a 316kWh NMC-P BESS with specifications reported in TABLE 14 (appendix A.1).
 - It is considered an average efficiency for ESS charging and discharging of 96% and 97%, respectively.
- Tunnel thruster rated power 700kW.

The focus for the ESS analysis is to provide support to the DC microgrid, especially during shooting and heave of the trawl as the PTI/PTO power response (dP/dt) limits the ability of following the DC grid load variations. Also, the fuel consumption reduction by use of the ESS is analysed.

6.2. Reference system operation without ESS

First a reference system operation without ESS is considered to quantify the benefit of installing an ESS in the system. It is assumed that the PTI/PTO keeps the same dynamics/response, and the AC grid connection supplies the required power to support the DC microgrid load in addition to the PTI/PTO power. In addition, it is assumed that a 15% share of the average DC microgrid load is supplied by the AC grid connection. An average conversion efficiency from AC grid to DC microgrid of 94% is considered.

FIGURE 6-2 shows the Trawler reference operation profile without ESS. For the 48 hours operation profile, it is estimated a main engine fuel consumption of about 26.75 tons and an auxiliar generator fuel consumption of 2.15 tons, giving a total fuel consumption of 28.9 tons for the 48 hours operation.

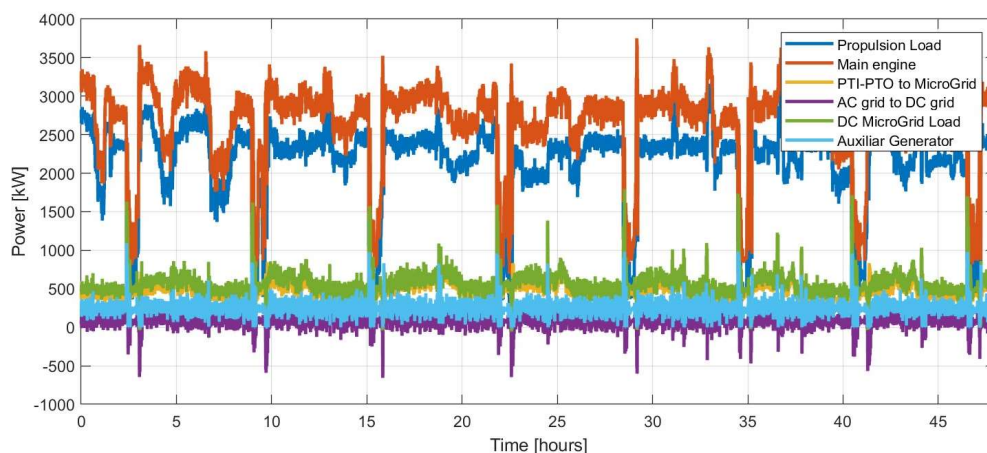


FIGURE 6-2 TRAWLER REFERENCE OPERATION WITHOUT INSTALLED ESS.

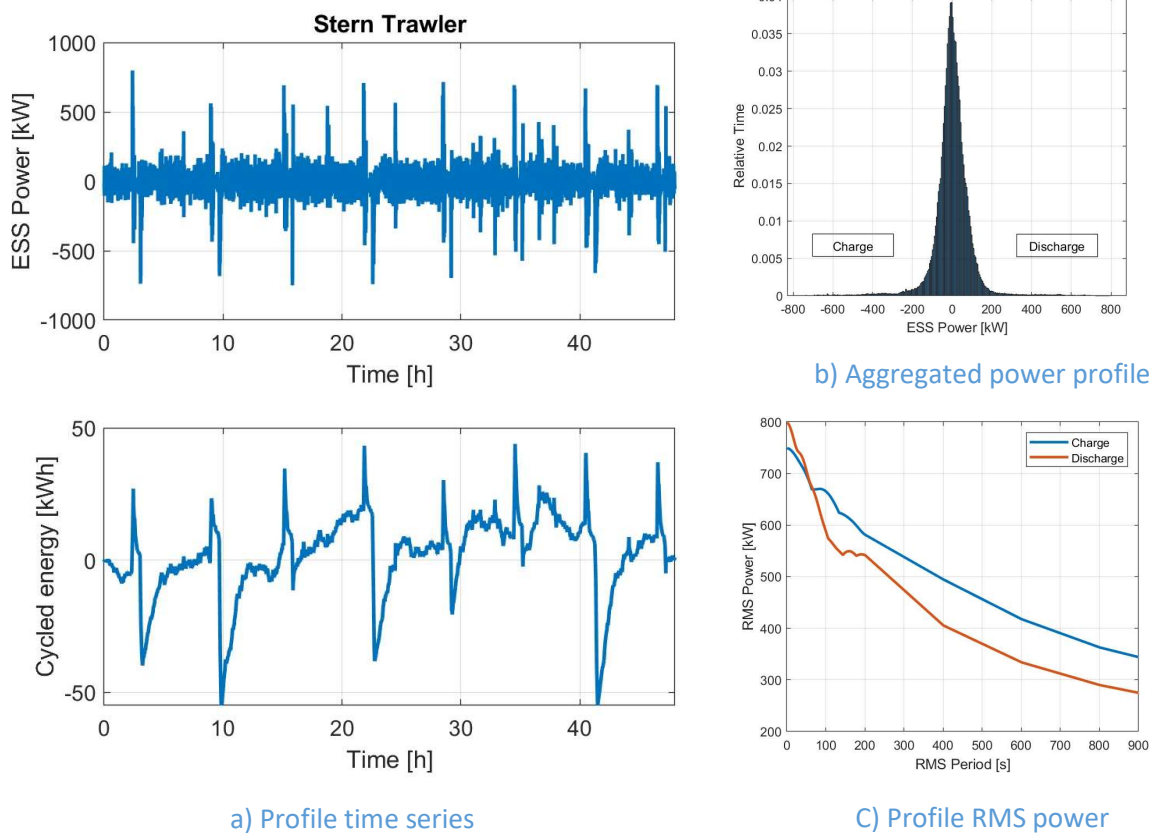


FIGURE 6-3 STERN TRAWLER ESS REFERENCE PROFILE.

6.3.ESS case study

The first case to be analysed is the reference operation profile associated to the provided log data presented in appendix A.4, FIGURE A-9. By installing the ESS and following the operating profile of FIGURE A-9, it is estimated a main engine fuel consumption of about 27.61 tons for the 48 hours operation, which represents a fuel consumption reduction of about 4.46%.

FIGURE 6-3 shows the stern trawler reference ESS profile derived from the log data. From the considered trawler ESS profile, the following ESS requirements can be obtained:

- Minimum needed energy: 98.8 kWh
- Max. discharge power: 798.42 kW (peak), 560.74 kW (cont.)
- Max. charge power: 749.16 kW (peak), 643.93 kW (Cont.)
- Energy throughput: 169.85 MWh
- Equivalent Active days per year: 239.89 days

6.4. Optimal BESS solution

The ESS sizing for the stern trawler reference ESS profile has been estimated for all the considered battery technologies to establish the optimal BESS solution in this case. FIGURE 6-4 shows the BESS sizing criteria against the design lifetime for different battery technologies/chemistries and for supercapacitors. It can be noted that the sizing criteria differs from one technology to other. For this profile, the sizing of higher energy density technologies is ruled by the power capability criteria (peak or continuous power), while for high power density technologies, the main criterion is to ensure sufficient remaining capacity at end of the design lifetime (EDL).

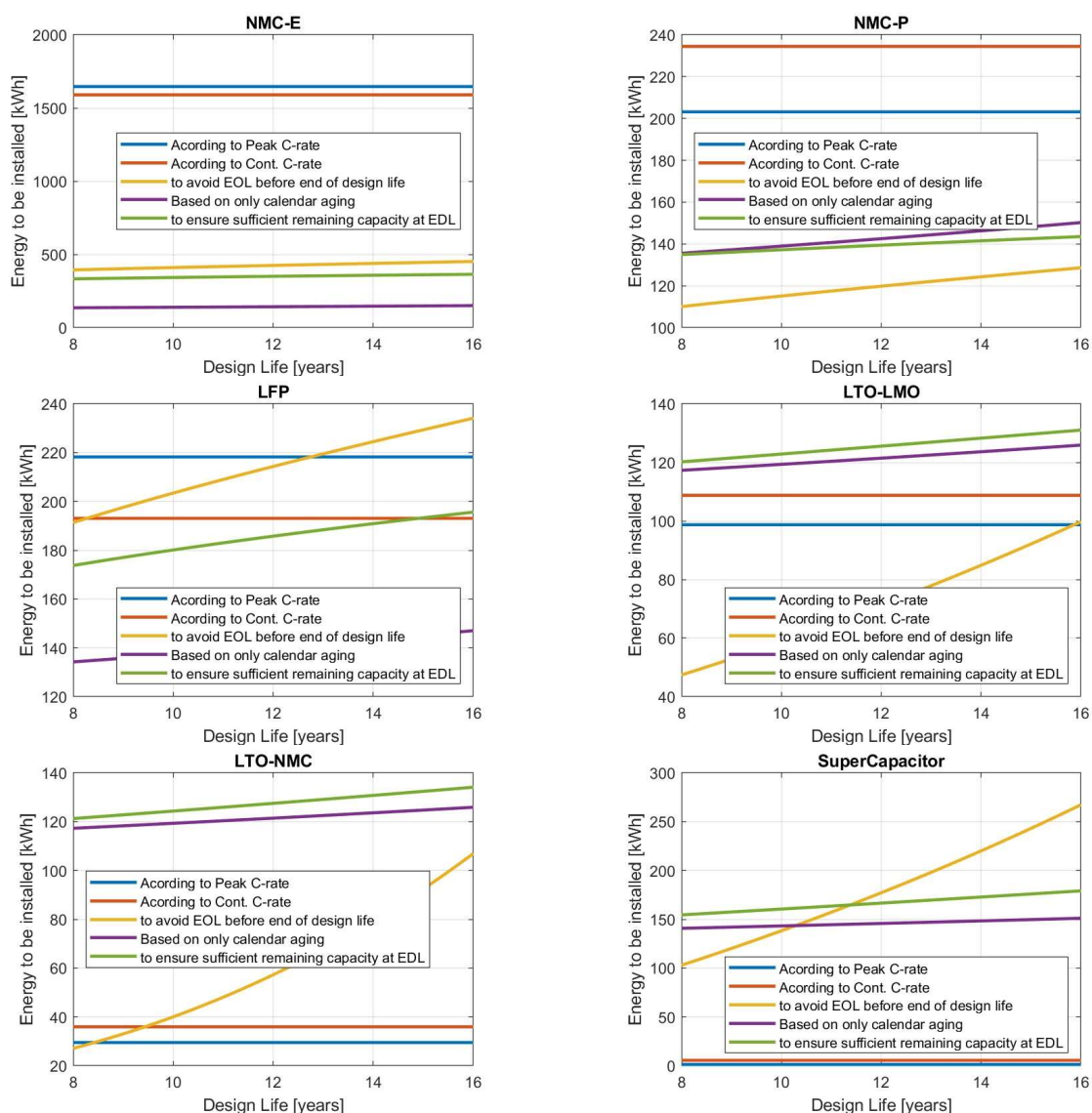


FIGURE 6-4 TRAWLER CASE: BESS-ONLY SIZING RESULTS AGAINST ESS DESIGN LIFETIME FOR DIFFERENT BATTERY TECHNOLOGIES/CHEMISTRIES.

TABLE 11 TRAWLER CASE: BESS-ONLY SIZING RESULTS FOR 10 YEARS ESS DESIGN LIFETIME.

Technology	NMC-E	NMC-P	LFP	LTO/LMO	LTO/NMC	SC
Required Energy [kWh]	1646.11	234.44	218.24	122.85	124.35	160.48
BESS Cost [k€]	658.45	164.11	76.38	135.13	174.09	802.42
BESS Volume [m³]	8.611	2.596	2.902	1.092	3.693	32.982
BESS Weight [Tons]	10.265	2.987	3.193	2.321	4.859	23.444
SOH at EDL [%]	96.175	95.71	84.32	89.37	88.29	82.09
Sizing Criteria	Peak. C-rate	Cont. C-rate	Peak. C-rate	Ensure sufficient remaining capacity at EDL		

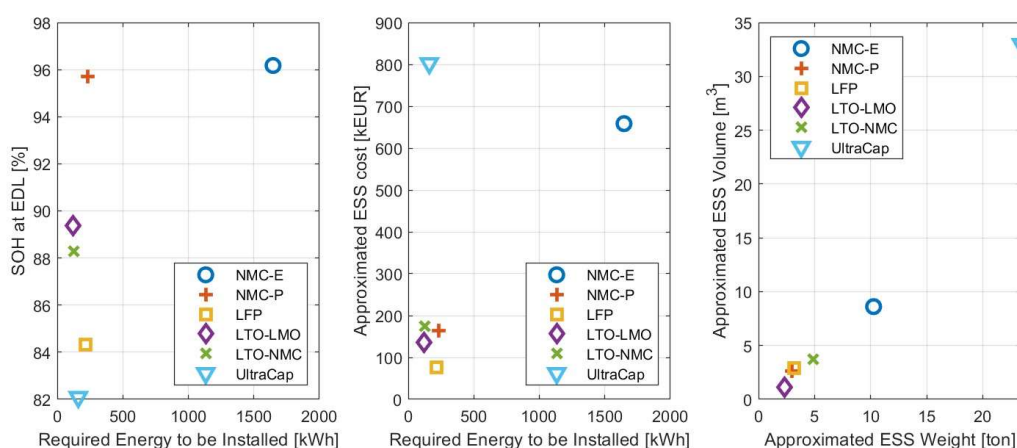


FIGURE 6-5 TRAWLER CASE: COMPARISON OF BESS-ONLY SIZING RESULTS FOR DIFFERENT BATTERY TECHNOLOGIES/CHEMISTRIES TARGETING A BESS DESIGN LIFETIME OF 10 YEARS.

FIGURE 6-5 shows the BESS-only sizing results for different battery technologies/chemistries targeting a BESS design lifetime of 10 years, while TABLE 11 summarizes those results. It can be noted that LFP, and LTO-LMO technologies provides the best trade-off between BESS cost, volume, and weight.

6.5. HESS solution: Combination of BESS and Supercapacitors

Results for HESS solutions based on batteries combined with supercapacitors are presented in this section. The combinations of SC with all battery technologies/chemistries from [TABLE 3](#) have been checked but only relevant ones are reported in this section.

First, a combination of LFP batteries with SC is investigated, as LFP batteries provides the lowest BESS-only solution. FIGURE 6-6 shows the main HESS sizing results for combination of Li-ion LFP batteries and supercapacitors. It can be noted that a reduction on cost, volume and weight can be achieved when installing SC capacities smaller than 1 kWh, with the optimal SC capacity around 0.2kWh, having a reduction of LFP BESS capacity of around 13kWh (from 217kWh to around 204 kWh).

FIGURE 6-7 shows the pareto optimality of required SC energy, HESS cost, volume, and weight versus required BESS installed energy for the combination of supercapacitors with NMC-P batteries (FIGURE 6-7a) and LTO-LMO batteries (FIGURE 6-7b). It can be noted that HESS solutions are not convenient for these combinations.

The combination of NMC-E batteries with supercapacitors also is investigated, as BESS-only solutions based on NMC-E batteries are limited by the peak C-rate, so supercapacitor may bring benefits to reduce NMC-E energy capacity. FIGURE 6-8 shows the main HESS sizing results for combination of Li-ion NMC-E batteries and supercapacitors. It can be noted that a reduction on cost, volume and weight can be achieved for these HESS solutions, having its minimums at different SC capacities.

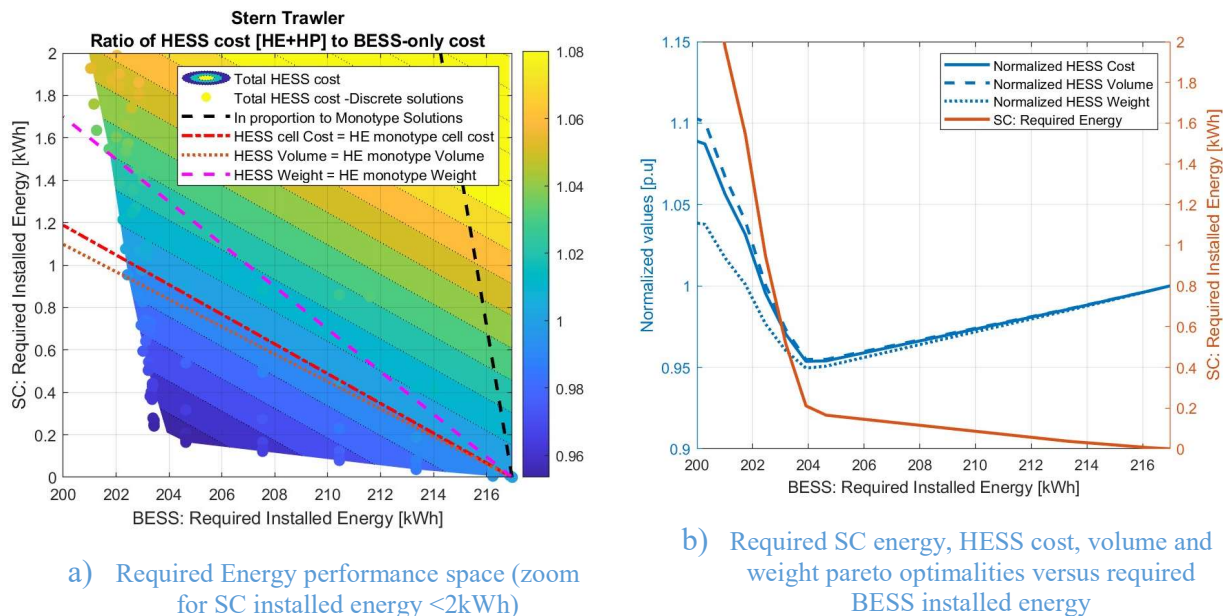
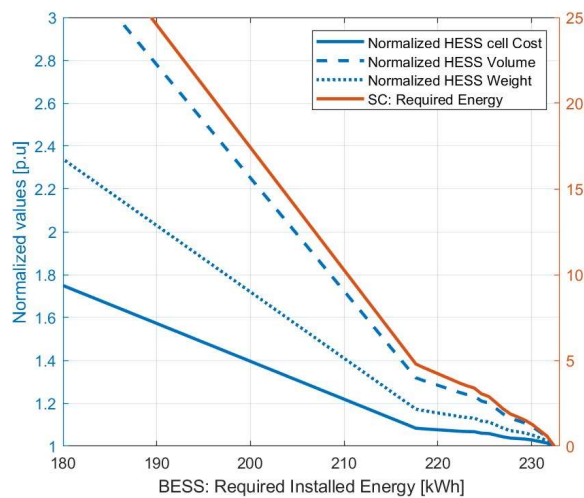
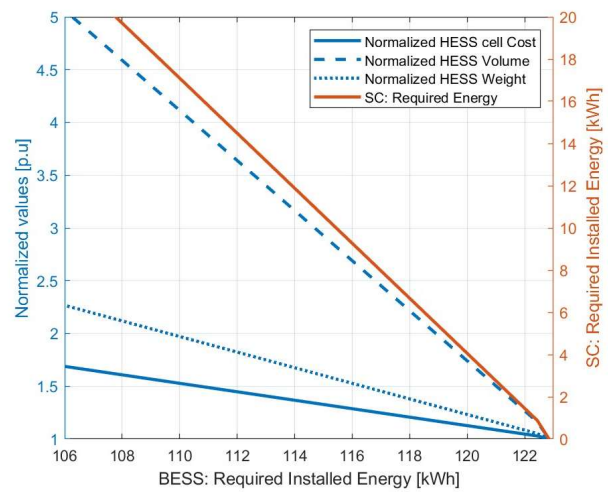


FIGURE 6-6 TRAWLER CASE: HESS SIZING RESULTS FOR COMBINATION OF LI-ION LFP BATTERIES AND SUPERCAPACITORS.

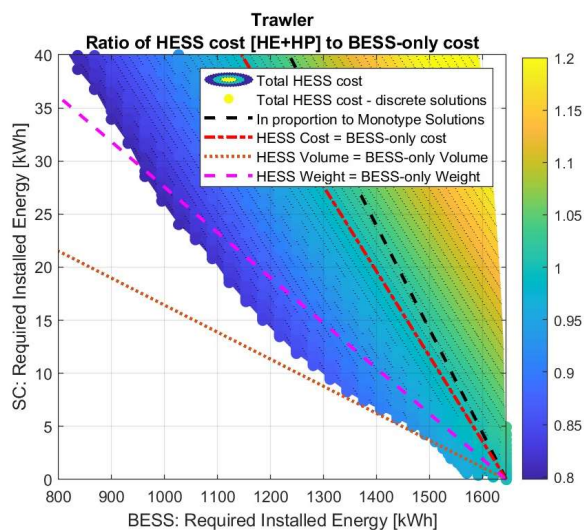


a) Combination of NMC-P Batteries with Supercapacitors

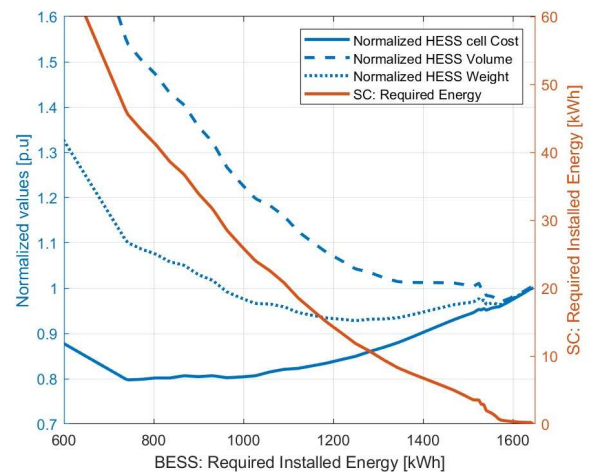


b) Combination of LTO-LMO Batteries with Supercapacitors

FIGURE 6-7 TRAWLER CASE: HESS SIZING RESULTS FOR COMBINATION OF LI-ION NMC-P AND LTO-LMO BATTERIES WITH SUPERCAPACITORS. REQUIRED SC ENERGY, HESS COST, VOLUME, AND WEIGHT PARETO OPTIMALITY VERSUS REQUIRED BESS INSTALLED ENERGY.



a) Required Energy performance space (zoom for SC installed energy <40kWh)



b) Required SC energy, HESS cost, volume and weight pareto optimalities versus required BESS installed energy

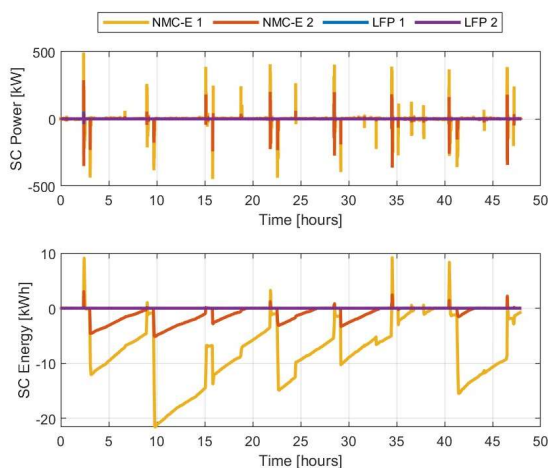
FIGURE 6-8 TRAWLER CASE: HESS SIZING RESULTS FOR COMBINATION OF LI-ION NMC-E BATTERIES AND SUPERCAPACITORS.

TABLE 12 TRAWLER CASE: HESS SIZING RESULTS FOR BESS COMBINED WITH SC.

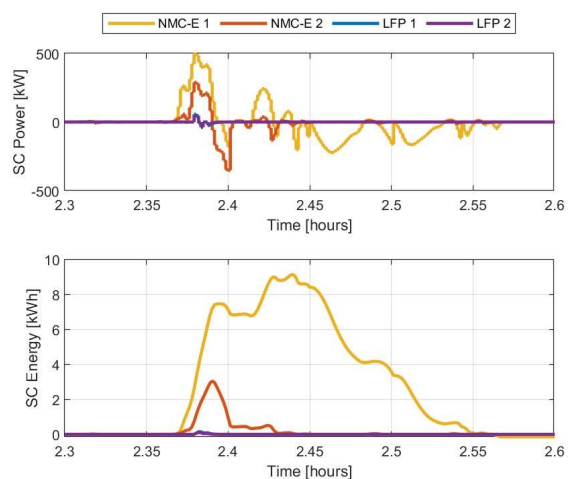
<i>Solution</i>		Ref. BESS-Only		HESS Best trade-off			
<i>Required Energy [kWh]</i>	<i>BESS Tech</i>	LFP	LTO-LMO	LFP		NMC-E	
	BESS	218.24	122.85	203.46	204.64	740.6	1248.8
	SC	--	--	0.2412	0.1651	45.71	11.88
<i>HESS Cost [k€]</i>		76.38	135.13	72.418	72.448	524.79	558.93
<i>HESS Volume [m³]</i>		2.902	1.092	2.755	2.755	13.27	8.97
<i>HESS Weight [Tons]</i>		3.193	2.321	3.012	3.018	11.29	9.52

For small SC energies (<1kWh), the volume can be reduced up to 5% compared with NMC-E BESS-only solution, while weight can be reduced up to 10% with SC capacities of around 11 kWh (however volume increases by around 8%). The ESS cost can be reduced by around 20% compared to an NMC-E BESS-only solution by installing around 45kWh SC but volume and weight increase by 45% and 10%, respectively.

TABLE 12 summarizes the best HESS solutions when the BESS is combined with a SC. While, FIGURE 6-9 shows the SC waveforms of the HESS selected solutions for combination of Li-ion batteries and supercapacitors, for the 48-hours series (FIGURE 6-9a) and a zoom when SC peak energy is reached (FIGURE 6-9b).



a) 48 hours profile cycle

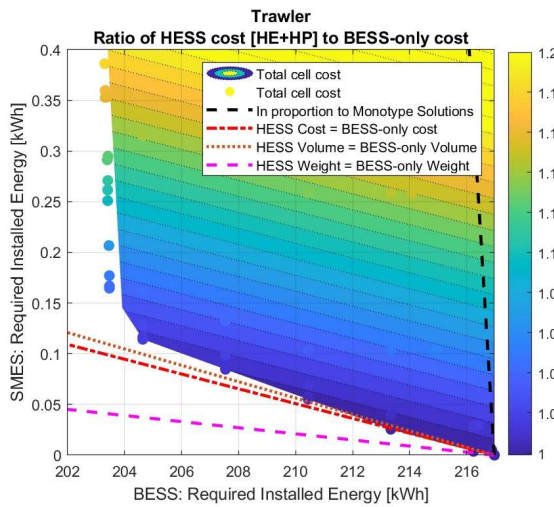


b) Zoom when SC peak energy is reached for most of the solutions.

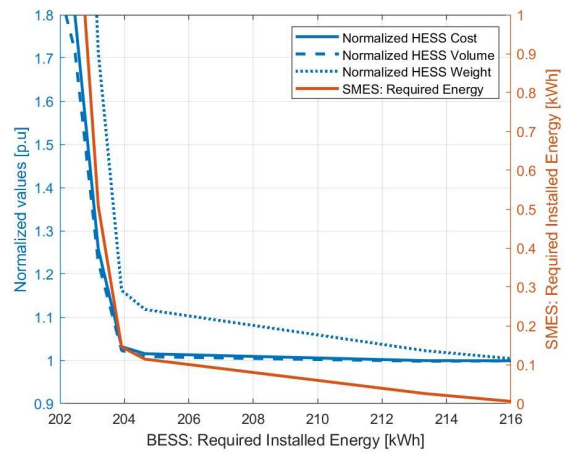
FIGURE 6-9 TRAWLER CASE: SC WAVEFORMS OF THE HESS SELECTED SOLUTIONS FOR COMBINATION OF BATTERIES WITH SUPERCAPACITORS.

6.6.HESS solution: Combination of BESS and SMES

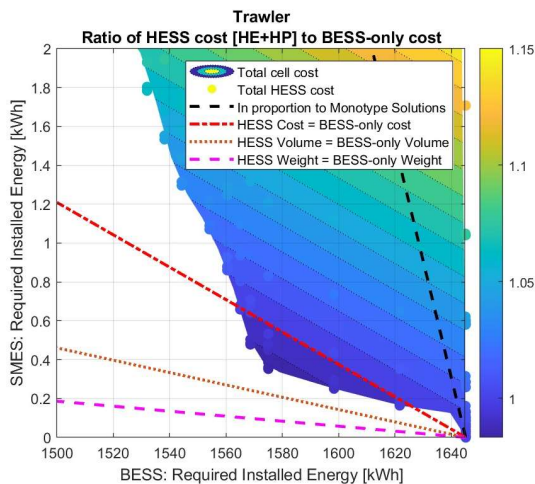
A similar procedure as for the previous case was followed for the HESS solution combining BESS with SMES. However, for the case of SMES, the HESS cost is evaluated against the ship lifetime (30 years), instead of the ESS design life (10 years), as the SMES degradation is negligible. Thus, the total cost of the HESS solution will include the BESS replacements to the ship lifetime (3 replacements), and therefore the reference cost of BESS-only solution will be three times the reported cost in TABLE 11.



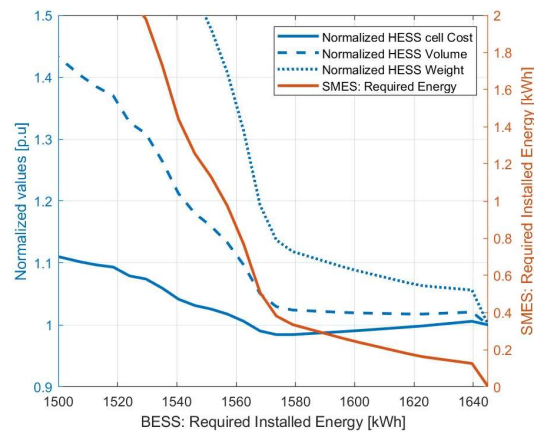
a) LFP batteries and SMES. Required Energy performance space (zoom for SMES installed energy <0.4kWh).



b) LFP batteries and SMES. Required SMES energy, HESS cost, volume and weight pareto optimalities versus required BESS installed energy.



c) NMC-E batteries and SMES. Required Energy performance space (zoom for SMES installed energy <2kWh)



d) NMC-E batteries and SMES. Required SMES energy, HESS cost, volume and weight pareto optimalities versus required BESS installed energy

FIGURE 6-10 TRAWLER CASE: HESS SIZING RESULTS FOR COMBINATION OF LI-ION BATTERIES AND SMES.

TABLE 13 TRAWLER CASE: HESS SIZING RESULTS FOR BESS COMBINED WITH SMES.

<i>Solution Target:</i>		<i>Ref. BESS-Only</i>		<i>HESS Best trade-off</i>		
	<i>BESS Tech</i>	<i>LFP</i>	<i>LTO-LMO</i>	<i>LFP</i>		<i>NMC-E</i>
<i>Required Energy [kWh]</i>	<i>BESS</i>	218.24	122.85	216.24	213.34	1575
	<i>SMES</i>	--	--	0.0038	0.0255	0.3528
<i>HESS Cost (30 years) [k€]</i>		229.14	405.39	227.6	227.7	1940.8
<i>HESS Volume [m³]</i>		2.902	1.092	2.881	2.879	8.820
<i>HESS Weight [Tons]</i>		3.193	2.321	3.182	3.245	11.534

FIGURE 6-10 shows the HESS sizing results for combination of Li-ion Batteries and SMES. For this case, the combination with SMES does not bring noticeable benefits. For HESS solutions combining LFP batteries and SMES, it is possible to reduce the LFP-BESS size from around 218 kWh to 204 kWh by installing a 0.1kWh SMES, while keeping similar cost and volume but with an increment of around 15% in weight compared to LFP-BESS only solution. On the other hand, a HESS solutions combining NMC-E batteries and SMES can reduce the BESS size by around 80 kWh while keeping the same cost but always with higher volume and weight.

TABLE 13 summarizes the best HESS solutions for BESS combined with SMES. It can be noted that the best HESS solutions cannot reduce the volume/weight of the BESS-only solution based on LTO-LMO batteries and the reduction in cost is marginal compared to LFP BESS-only solution, so the combination with SMES is not convenient for this application.

7. Conclusion

This document reports a preliminary assessment of combined storage systems for the selected marine applications within V-ACCESS project. Three marine power applications have been analysed: a full electric ferry, an offshore support vessel with active heave compensation and a stern trawler.

An ESS sizing methodology as well as a HESS design and evaluation framework have been introduced. Also, the relevant trade-offs between ESS requirements and functionalities have been estimated and sizing of battery only solutions has been performed for the most common Li-ion battery technologies available for marine applications. So, the optimal BESS solutions for each of the considered marine applications has been detected.

Two hybrid energy storage solutions have been analysed, the combination of Li-ion batteries with supercapacitors and with SMES. The preliminary assessment of combined storage systems has been carried out considering the optimal BESS-only solutions as reference solutions, regarding cost, volume, and weight of the ESS.

It has been shown that the combination of batteries with supercapacitors can bring benefits in terms of reduction of cost, weight, and volume for the three analysed marine applications. However, the use of SMES in the HESS may only be partially beneficial regarding the HESS cost for the offshore support vessel with active heave compensation system.



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Appendix

A. Reference Input data

A.1. Reference Battery Systems

TABLE 14 shows the reference BESS configurations provided by Vard Electric for the analysed applications. All the three BESS are based on the module orca energy from Corvus Energy, and a 70% usable energy is reported, which is associated with the usable BESS SOC range from 10% to 80%.

The BESS are the actual system installed in the vessel from the log data came from. However, no information about the expected annual usage of the vessel and/or the BESS sizing considerations was provided, making it difficult to find the rationalization behind the installed BESS energy for each vessel.

TABLE 14 REFERENCE BATTERY SYSTEM CONFIGURATIONS PROVIDED BY VARD ELECTRIC FOR THE ANALYSED APPLICATIONS.

Vessel Type	Battery Energy Storage System					DC-Link Voltage		System Voltage
	Installed Energy [kWh]	Max. Cont. Power [kW]	Installed Capacity [Ah]	Voltage [V _{DC}]				
				Min.	Max.	Min.	Max.	
Electric Ferry	2 x 678	2x1935	2 x 768	720	1000	840	930	840-930 V _{DC}
PSV	497	1500	512	800	1100	800	1100	690 V _{AC}
Trawler	315	600	512	510	700	510	700	440 V _{AC}

A.2. Single Line Diagrams for analysed Marine systems.

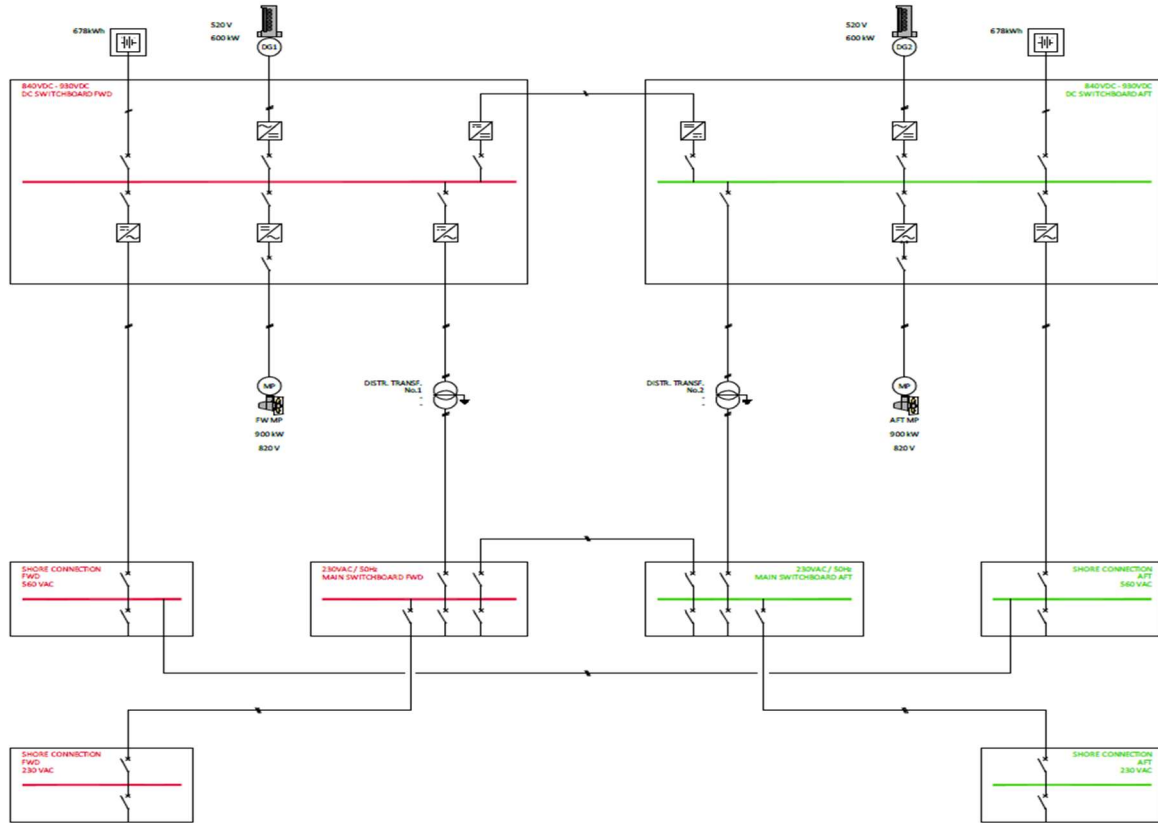


FIGURE A-1 REFERENCE SLD FOR ELECTRIC FERRY

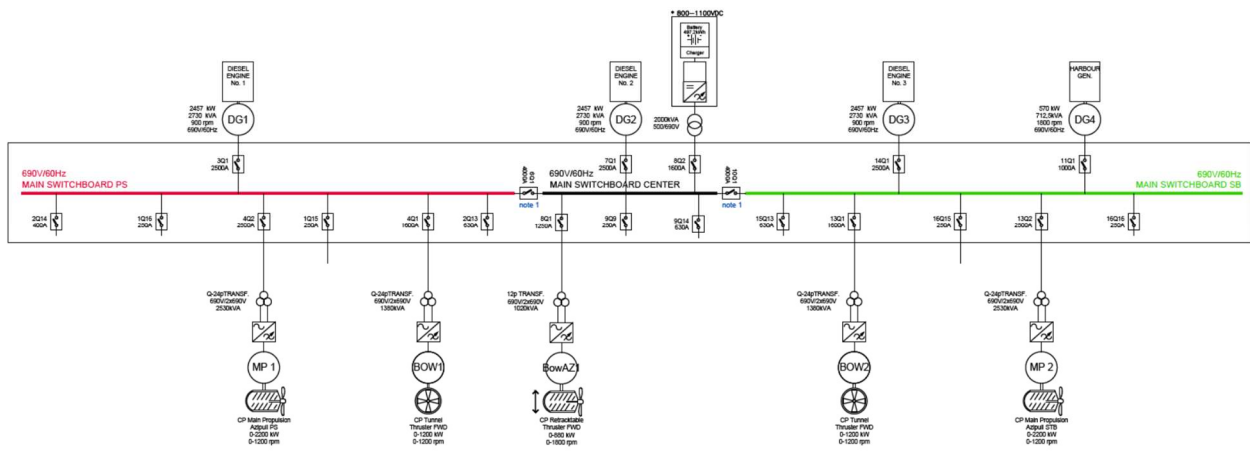


FIGURE A-2 REFERENCE SDL FOR OSV-AHC CASE.

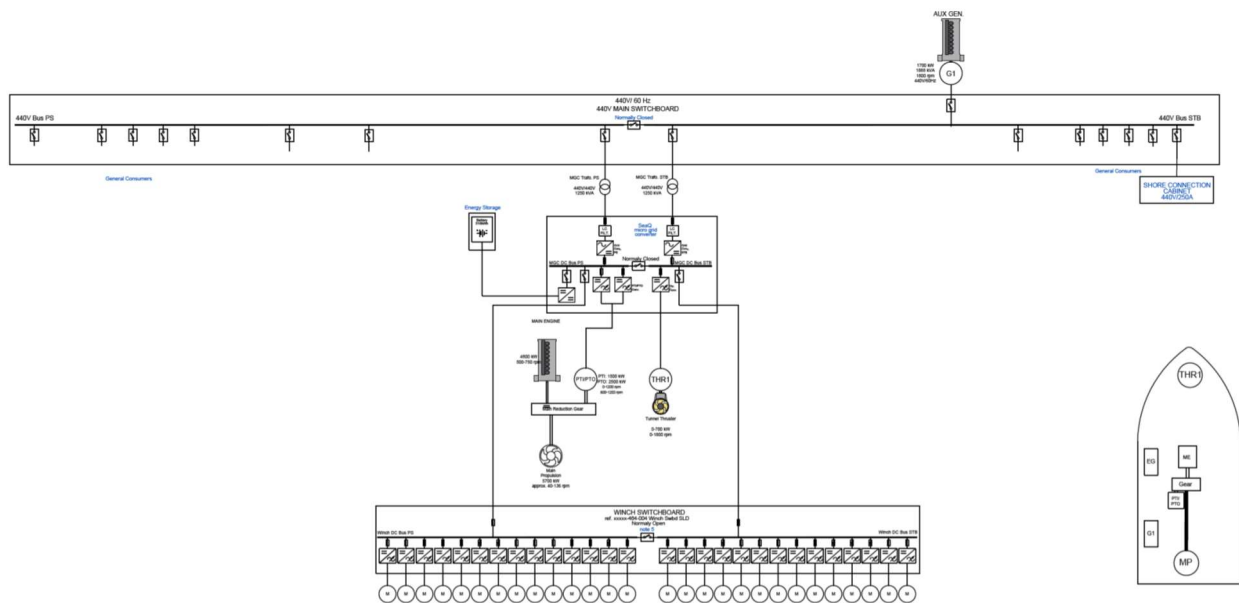


FIGURE A-3 REFERENCE SDL FOR TRAWLER CASE.

A.3. Provided data for definition of Electric Ferry mission profile.



FIGURE A-4 ELECTRIC FERRY LOG DATA PROVIDED BY VARD ELECTRIC

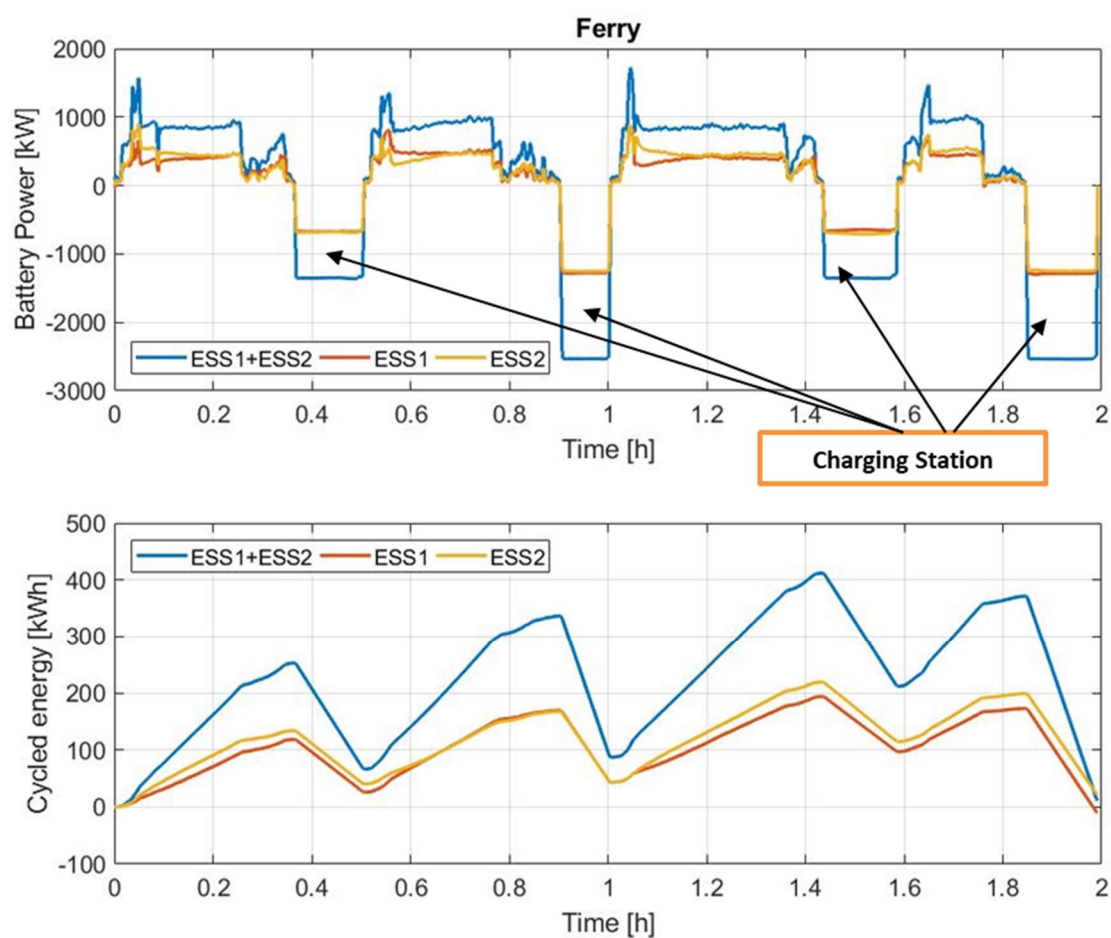


FIGURE A-5 ELECTRIC FERRY FUNDAMENTAL ESS POWER CYCLE.

A.4. Provided data for definition of OSV-AHC mission profile.

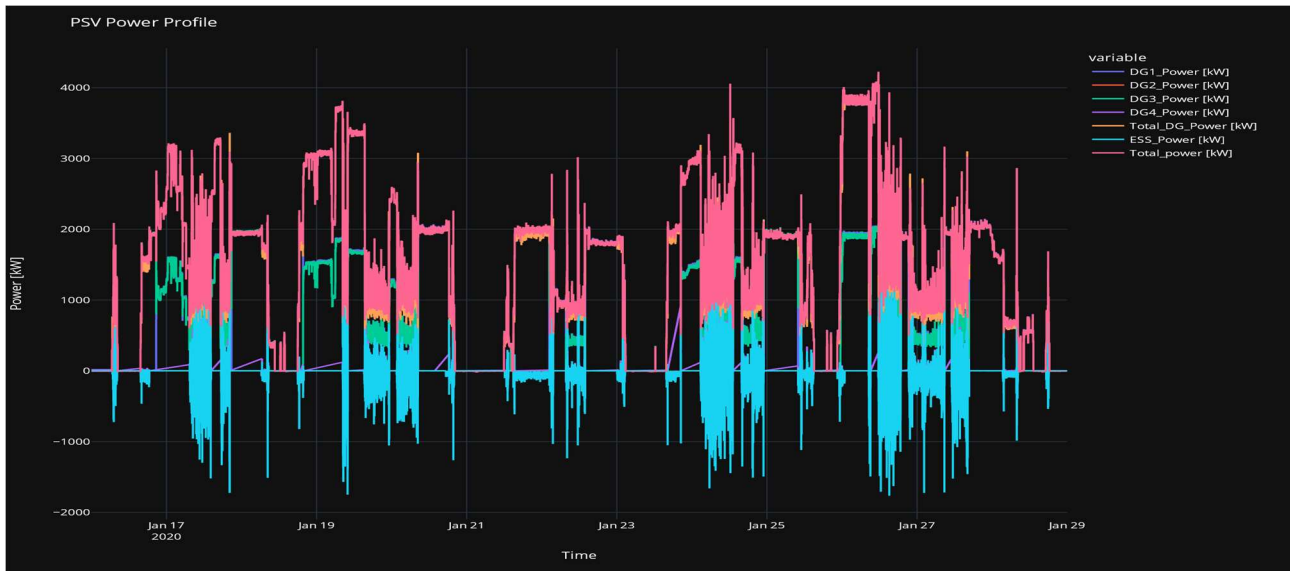


FIGURE A-6 PSV LOG DATA PROVIDED BY VARD ELECTRIC

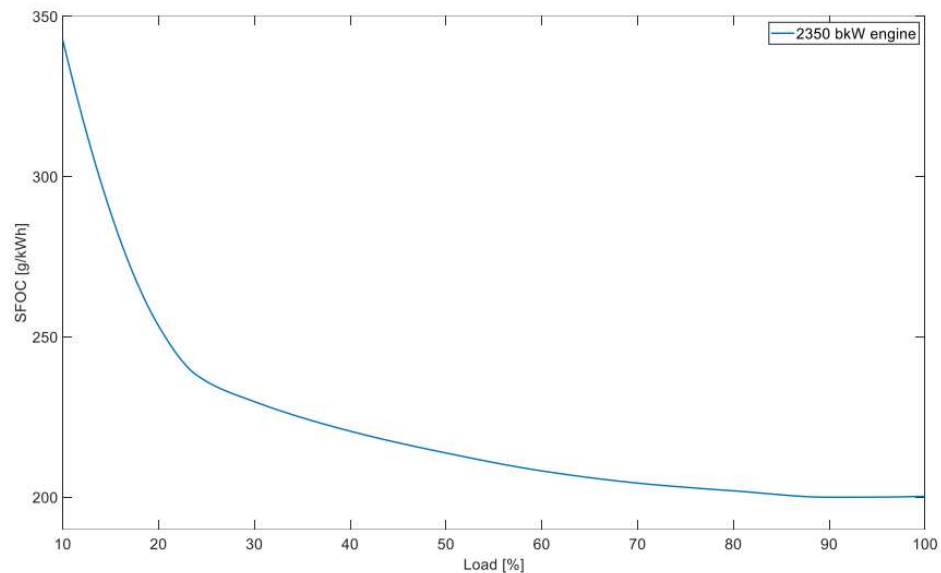


FIGURE A-7 REFERENCE SPECIFIC FUEL CONSUMPTION CURVE FOR GENERATORS PROVIDED BY VARD ELECTRIC.

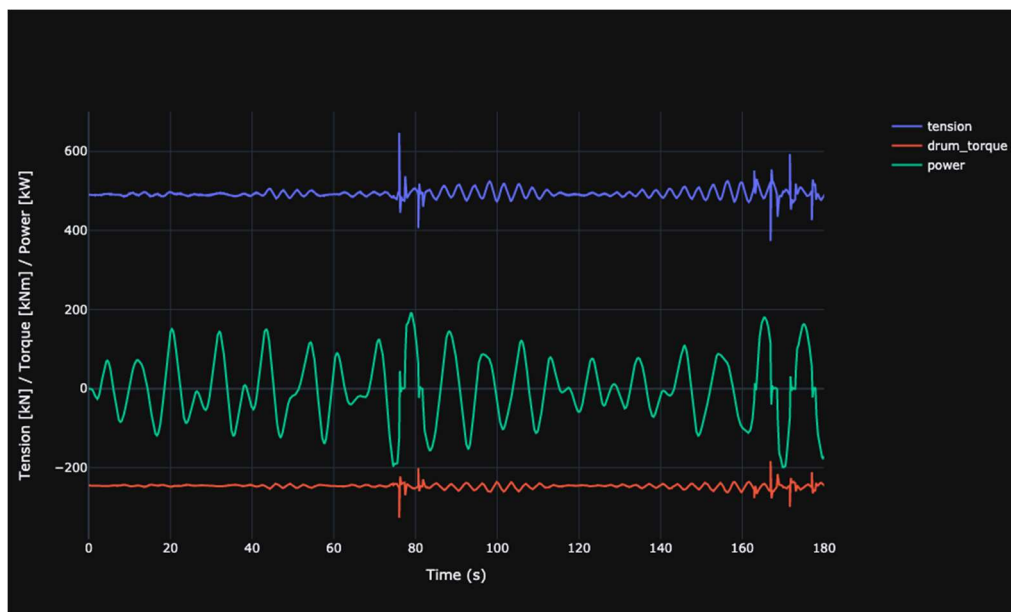


FIGURE A-8 ACTIVE HEAVE COMPENSATION SYSTEM SIMULATION PROVIDED BY SINTEF OCEAN

A.5. Provided data for definition of Trawler mission profile.

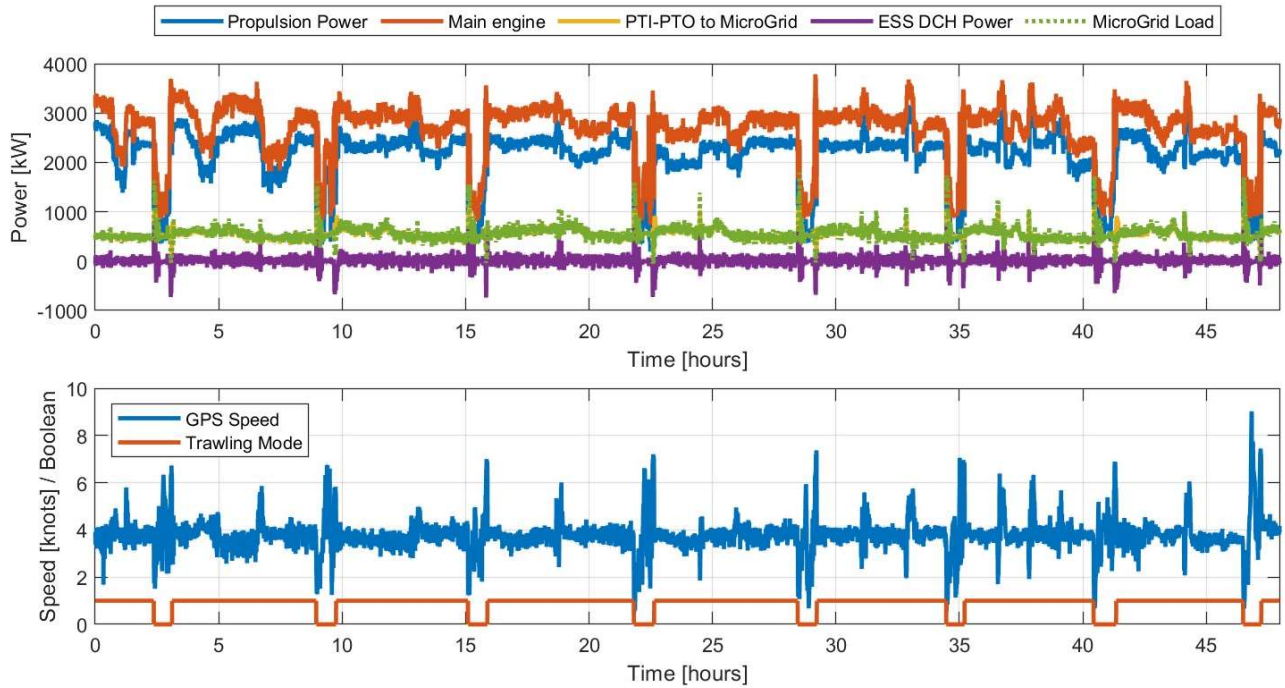


FIGURE A-9 TRAWLER LOG DATA PROVIDED BY VARD ELECTRIC

B. Additional figures and Results

B.1. Electric Ferry Case

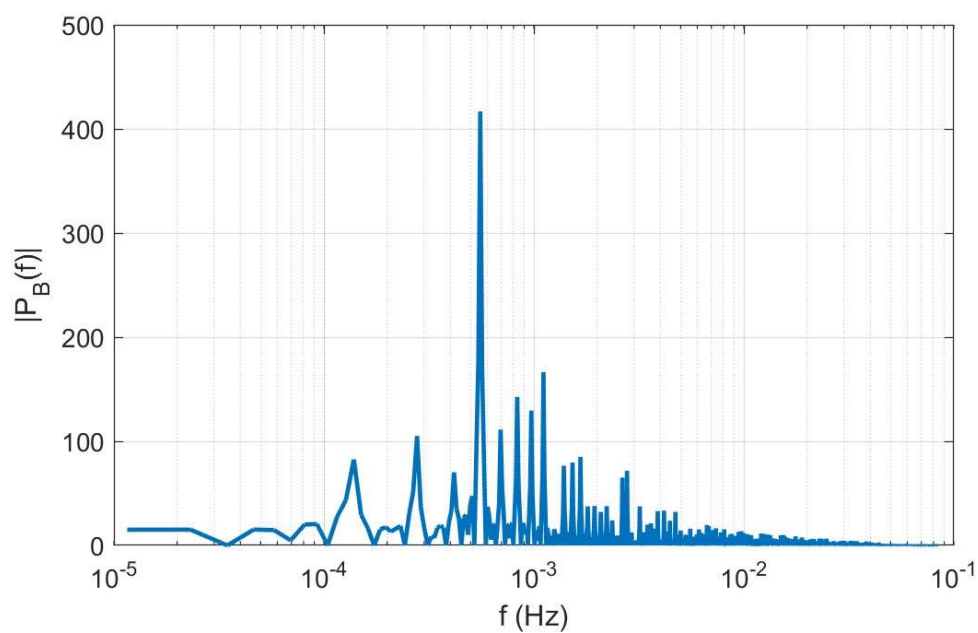


FIGURE B-1 ELECTRIC FERRY CASE: AMPLITUDE SPECTRUM OF POWER PROFILE.

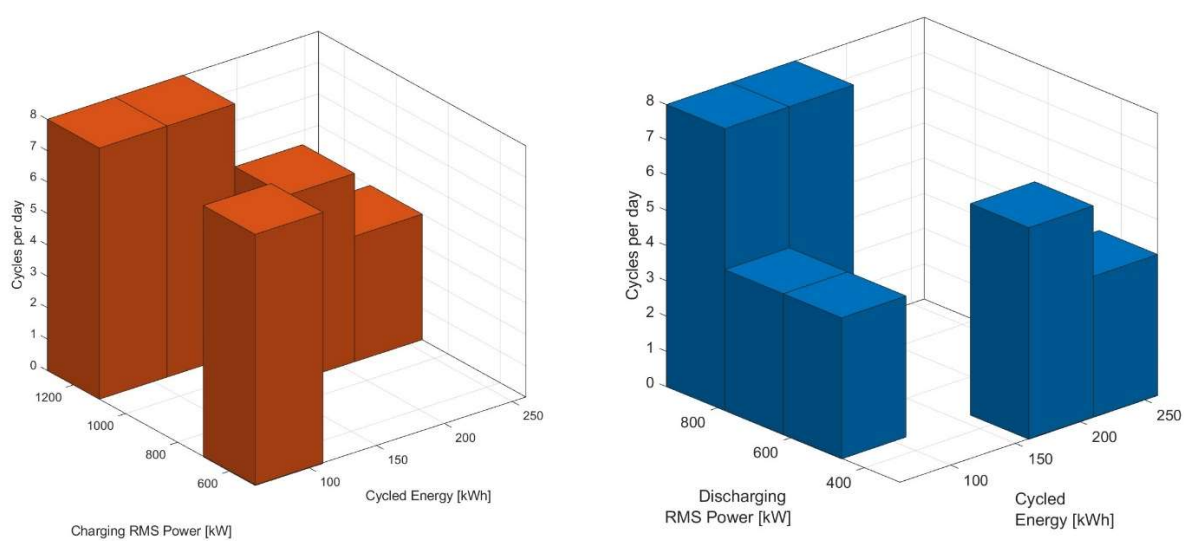


FIGURE B-2 CYCLING ANALYSIS FROM RAIN-FLOW ALGORITHM FOR ELECTRIC FERRY PROFILE.



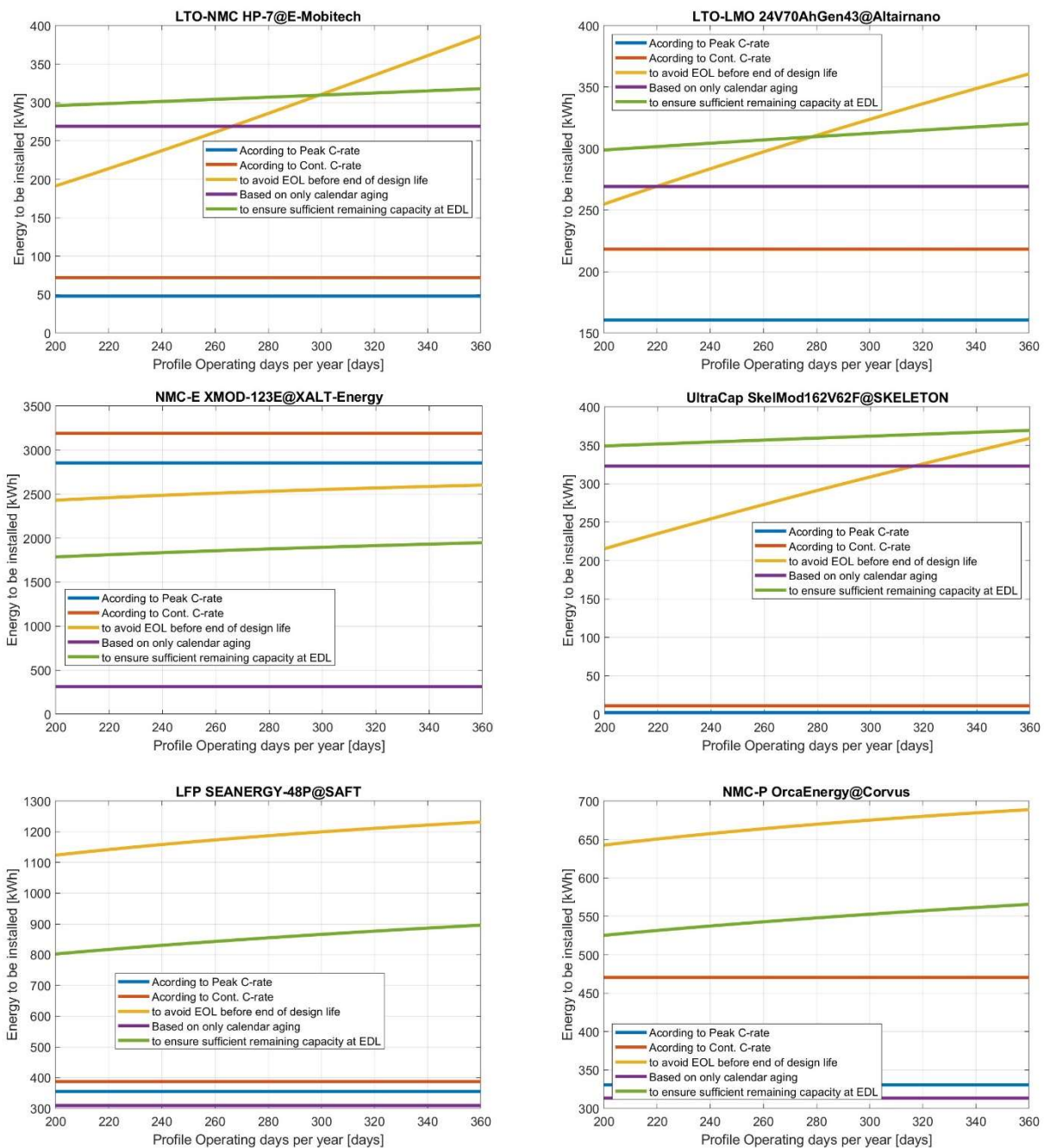


FIGURE B-3 ELECTRIC FERRY CASE: REQUIRED BESS ENERGY TO BE INSTALLED FOLLOWING DIFFERENT ESS SIZING CRITERIA VERSUS OPERATING DAYS PER YEAR. RESULTS FOR DIFFERENT BESS TECHNOLOGIES.

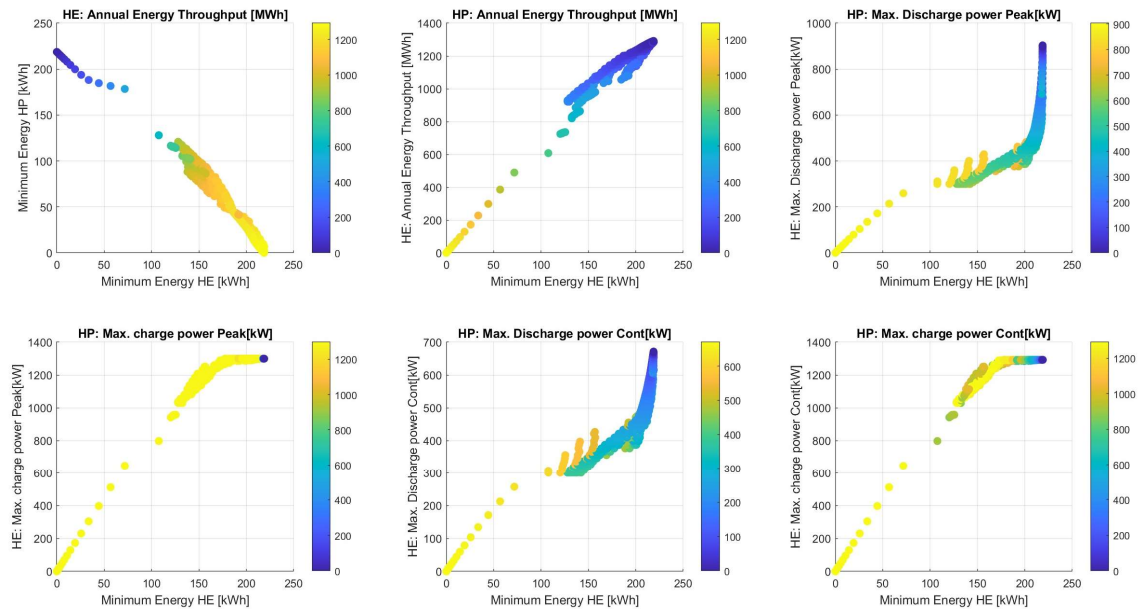


FIGURE B-4 ELECTRIC FERRY CASE: CORRELATION BETWEEN HESS-EMS MAPPED MULTI-DIMENSIONAL SUBSPACE REQUIREMENTS. EMS CHARGING STRATEGY: PRIORITIZING HE-ESS CHARGE.

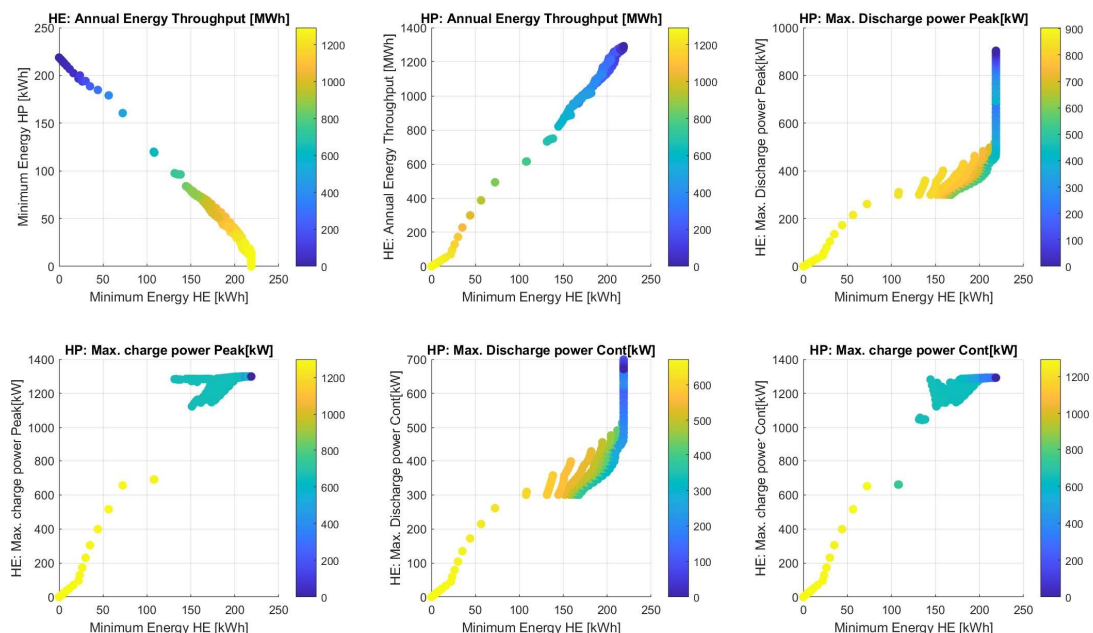


FIGURE B-5 ELECTRIC FERRY CASE: CORRELATION BETWEEN HESS-EMS MAPPED MULTI-DIMENSIONAL SUBSPACE REQUIREMENTS. EMS CHARGING STRATEGY: FORCING HP-ESS TO FULLY CHARGE DURING HESS DISCHARGING STATE.

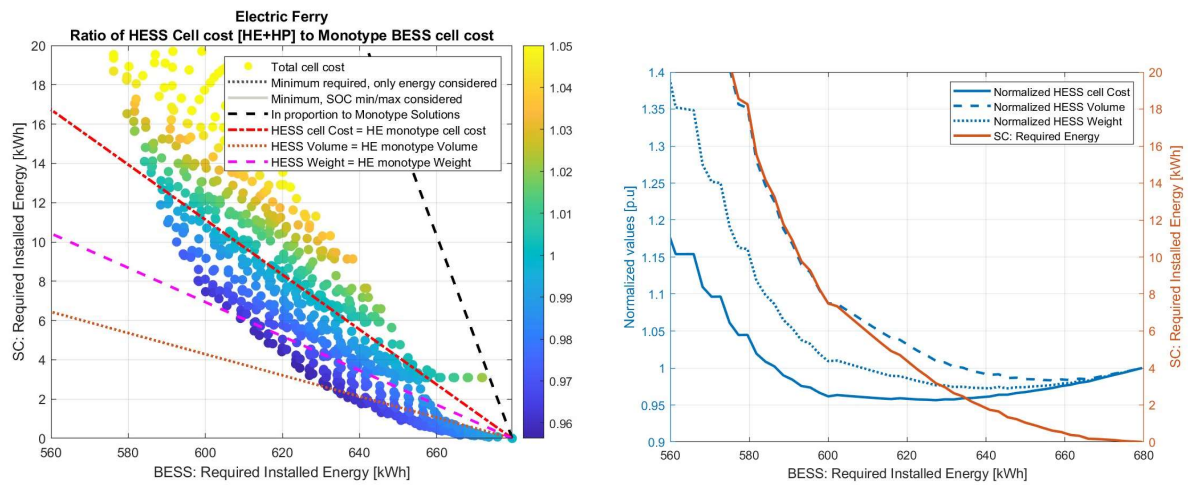


FIGURE B-6 ELECTRIC FERRY CASE: HESS SIZING RESULTS FOR COMBINATION OF LI-ION NMC-P BATTERIES AND SUPERCAPACITORS. EMS CHARGING STRATEGY: PRIORITIZING HE-ESS CHARGE.

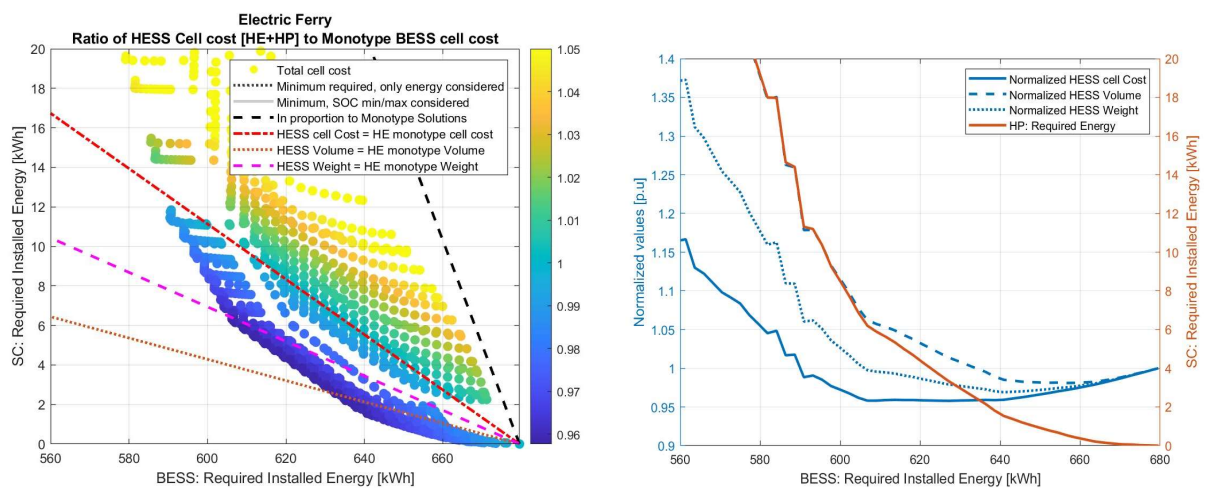


FIGURE B-7 ELECTRIC FERRY CASE: HESS SIZING RESULTS FOR COMBINATION OF LI-ION NMC-P BATTERIES AND SUPERCAPACITORS. EMS CHARGING STRATEGY: FORCING HP-ESS TO FULLY CHARGE DURING HESS DISCHARGING STATE.

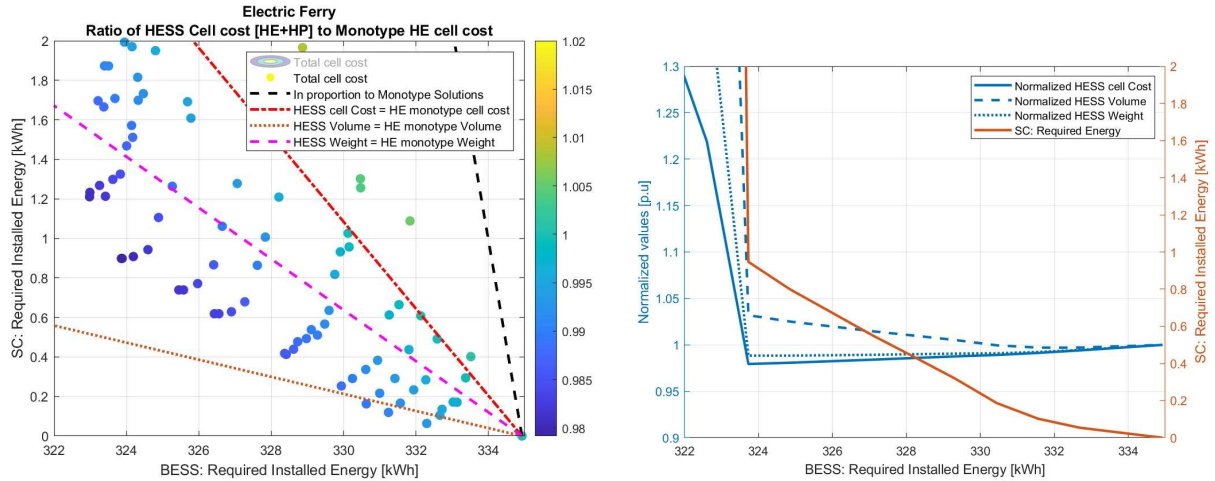


FIGURE B-8 ELECTRIC FERRY CASE: HESS SIZING RESULTS FOR COMBINATION OF LI-ION LTO-NMC BATTERIES AND SUPERCAPACITORS. EMS CHARGING STRATEGY: PRIORITIZING HE-ESS CHARGE.

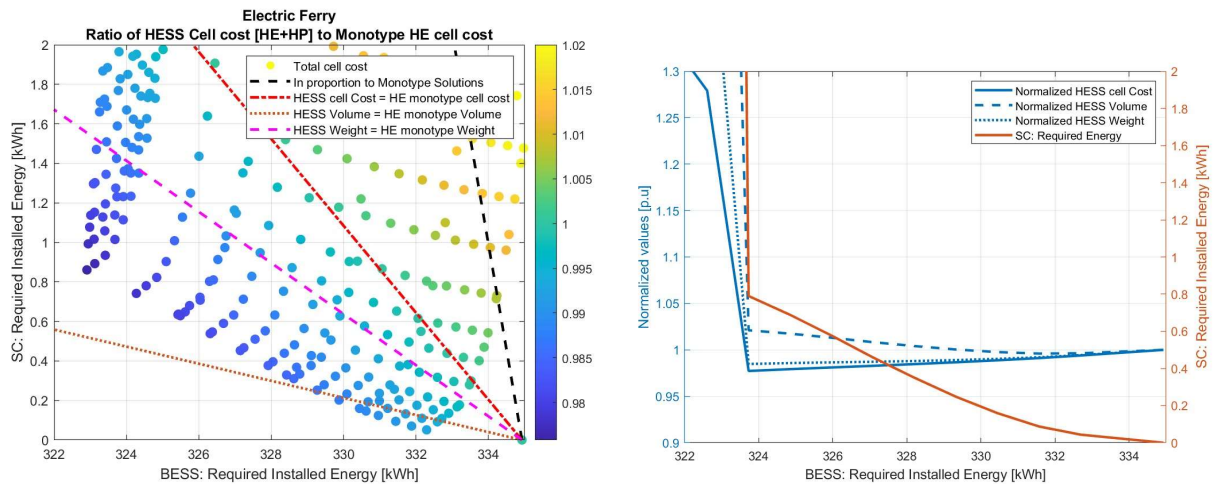
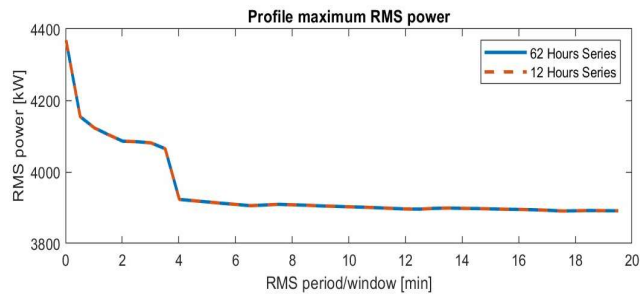
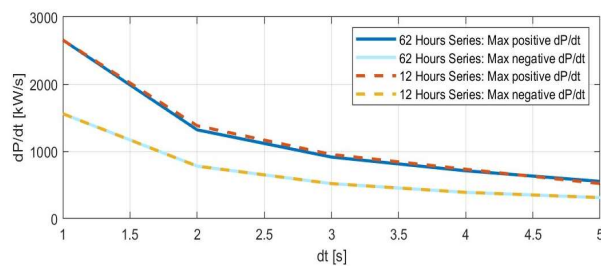


FIGURE B-9 ELECTRIC FERRY CASE: HESS SIZING RESULTS FOR COMBINATION OF LI-ION LTO-NMC BATTERIES AND SUPERCAPACITORS. EMS CHARGING STRATEGY: PRIORITIZING HP-ESS CHARGE DURING HESS CHARGE STATE.

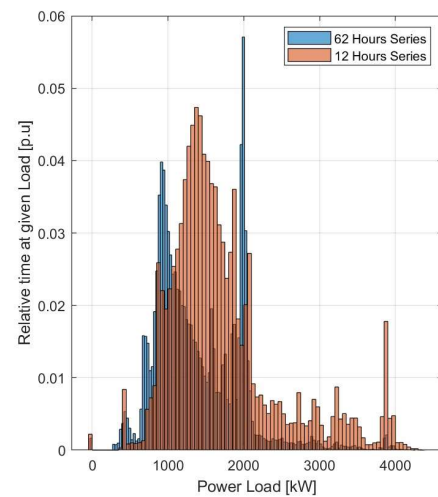
B.2. OSV-AHC case



a) MAXIMUM RMS POWER VERSUS RMS TIME WINDOW



c) PROFILE MAXIMUM DP/DT



b) AGGREGATED POWER PROFILE

FIGURE B-10 OSV-AHC STANDARD MISSION PROFILE COMPARISON.

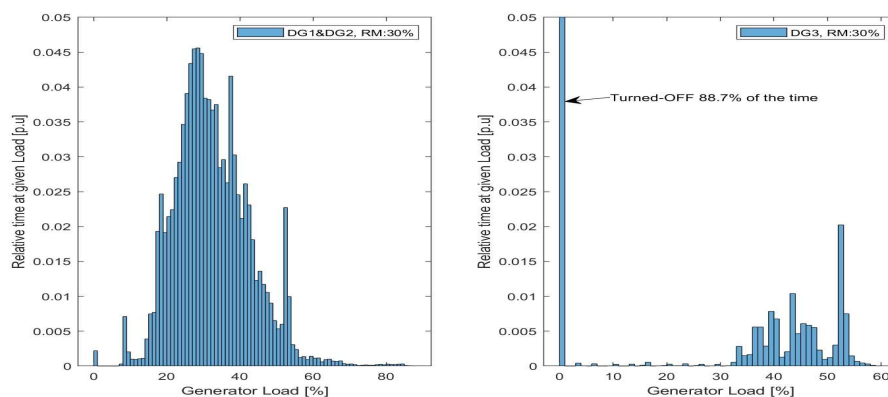


FIGURE B-11 OSV-AHC CASE: REFERENCE GENERATOR AGGREGATED LOAD PROFILES WHEN NO INSTALLED ESS.

OPTIMAL BESS SOLUTIONS

ESS AS SR+PS

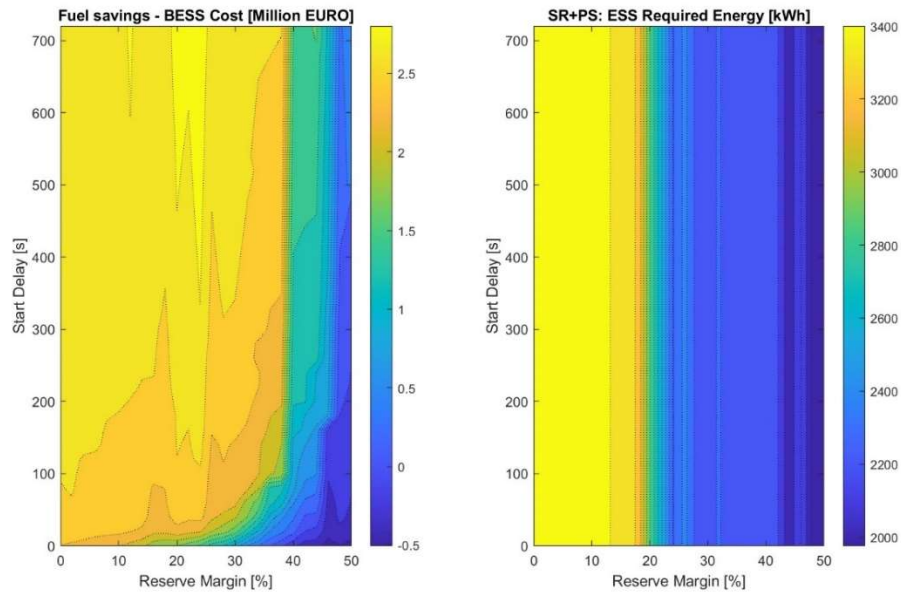


FIGURE B-12 OSV-AHC CASE: BESS AS SR+PS – SIZING RESULTS FOR NMC-E BATTERIES.

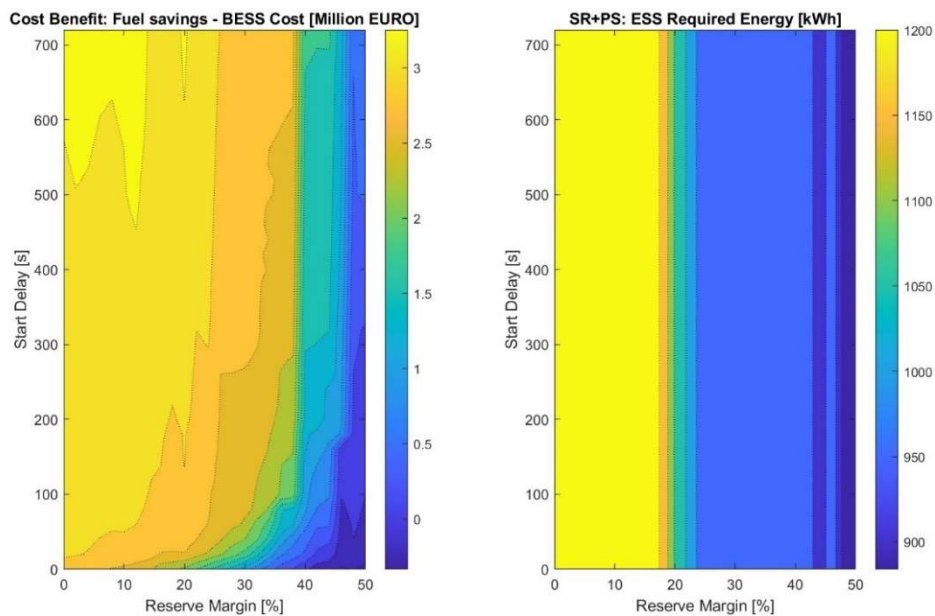


FIGURE B-13 OSV-AHC CASE: BESS AS SR+PS – SIZING RESULTS FOR NMC-P BATTERIES.



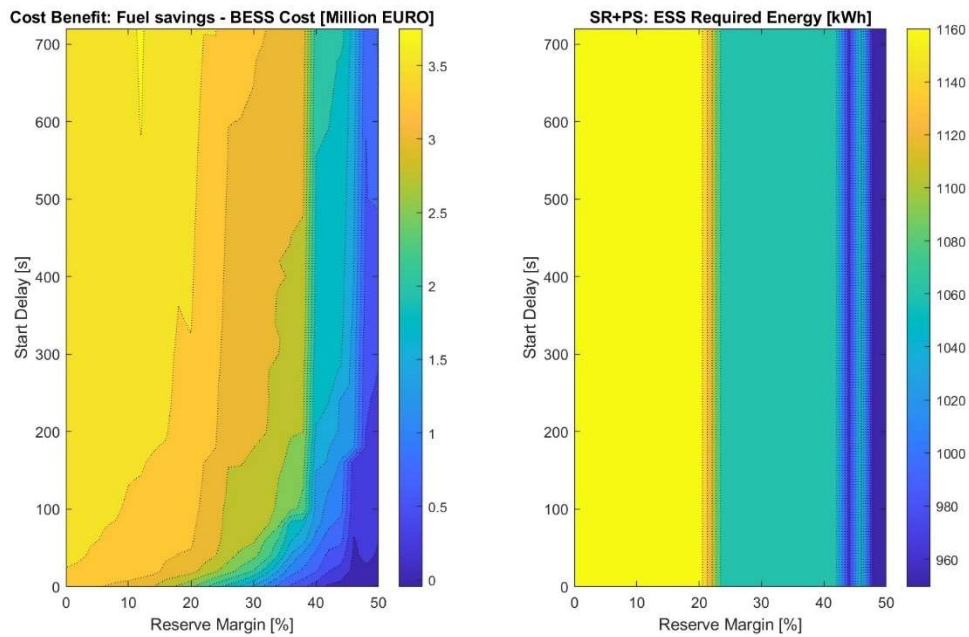


FIGURE B-14 OSV-AHC CASE: BESS AS SR+PS – SIZING RESULTS FOR LFP BATTERIES.

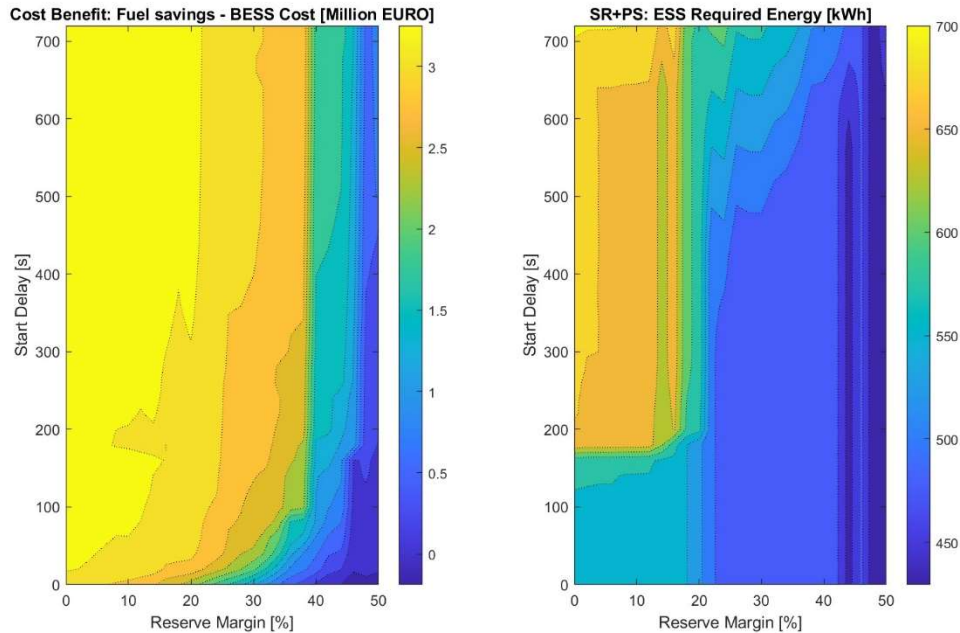


FIGURE B-15 OSV-AHC CASE: BESS AS SR+PS – SIZING RESULTS FOR LTO-LMO BATTERIES.

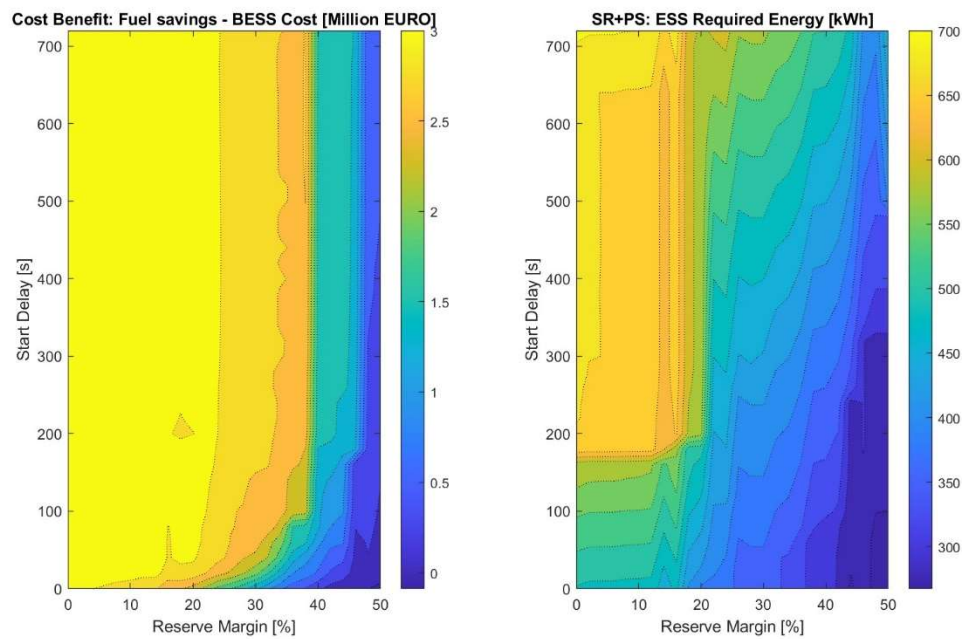


FIGURE B-16 OSV-AHC CASE: BESS AS SR+PS – SIZING RESULTS FOR LTO-NMC BATTERIES.

TABLE 15 OSV-ACH CASE: BESS-ONLY SIZING RESULTS WITH BEST TRADE-OFF BETWEEN ECONOMIC BENEFIT, ESS VOLUME AND ESS WEIGHT. CASES: ESS AS SR-ONLY AND ESS AS SR AND SL.

	Technology	NMC-E	NMC-P	LFP	LTO/LMO	LTO/NMC
ESS as SR only	Required Energy [kWh]	2290.12	987.67	1173.33	574.29	371.92
	BESS Cost [k€]	916.05	691.37	410.66	631.72	520.69
	BESS Volume [m ³]	11.98	10.94	15.601	5.104	11.04
	BESS Weight [Tons]	14.28	12.59	17.165	10.851	14.532
	Fuel consumption reduction [%]	5.55	5.55	8.455	8.455	6.652
	Economic Benefit [M€]	1.545	1.769	3.337	3.116	2.428
	Objective function value:	1.695	1.981	2	2	1.841
	DG reserve margin [%]	24	24	0	0	20
	ESS Sizing Criteria According to	Cont. CH C-rate	Peak DCH C-rate	Peak DCH C-rate	Cont. DCH C-rate	Ensure remaining capacity at EDL
ESS for SR and SL	Required Energy [kWh]	4393.8	987.67	1173.33	574.29	429.81
	BESS Cost [k€]	1757.5	691.37	410.66	631.72	601.73
	BESS Volume [m ³]	22.984	10.94	15.601	5.104	12.76
	BESS Weight [Tons]	27.3986	12.59	17.165	10.851	16.79
	Fuel consumption reduction [%]	8.0032	5.52	8.4017	8.402	6.585
	Economic Benefit [M€]	1.790	1.757	3.314	3.092	2.317
	Objective function value:	2	1.981	2	2	1.877
	DG reserve margin [%]	0	24	0	0	20
	SFC margin [%]	6	8	20	20	8
	ESS Sizing Criteria According to	Peak CH C-rate	Peak DCH C-rate	Peak DCH C-rate	Cont. DCH C-rate	Calendar aging