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Interoperable, modular and Smart hybrid energy STORage systeM for stationarY applications

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Deliverable Report

D3.1 – Report on the Design Optimization Framework of the Power Electronics Interfaces

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Publishable summary

The iSTORMY project aims at developing an interoperable and modular Hybrid Energy Storage System (HESS) by demonstrating various use cases and seamlessly interfacing the grid to provide multiple services. In this task, a fast co-design optimization and sizing framework for the modular hybrid HESS is developed based on the system simulation to find the optimal sizing of HESS components in terms of longer lifetime, higher efficiency, and lower cost. The system simulation is based on low- to medium-fidelity models of the battery modules and the power electronics (PE) interfaces, based on the specifications defined in WP1 and the modelling from WP2 and WP3. Also, a first iteration of the Energy Management Strategy (EMS) is developed in parallel with WP4 to ensure the co-design of the system. Different cell technologies and PE interfaces are considered in terms of high power and high energy battery pack to build the HESS and meet the load profile requirements. Based on a multi-objective genetic algorithm optimization, the optimal solutions are obtained and compared in terms of system cost over 10 years lifetime, system efficiency, battery lifetime, and PE interface lifetime. Finally, the iSTORMY solution is selected with the description of the battery packs (chemistry, capacity, first- or second-life batteries) and PE interface architecture, topology, and size.

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Abbreviations

Symbol / short name	
HESS	Hybrid Energy Storage System
PE	Power Electronics
WP	Work Package
EMS	Energy Management Strategy
HE	High Energy
HP	High Power
EEC	Electric Equivalent Circuit
LoFi	Low-Fidelity
LCOS	Levelized Cost of Storage
MTBF	Mean Time Between Failure
SoC	State of Charge
SoH	State of Health
DoD	Depth of Discharge
TCO	Total Cost of Ownership
COF	Co-Design Optimization Framework

1 Introduction

The iSTORMY project aims to develop an interoperable and modular Hybrid Energy Storage System (HESS) by demonstrating various use cases and seamlessly interface the grid to provide multiple services, such as a combination of load levelling, frequency regulation, and provision of backup power at minimum cost. The HESS consists of batteries (1st and 2nd life), power electronics, thermal management, and control systems. In order to fulfil the project objectives with reduced cost and higher efficiency for the system, a holistic co-design optimization framework (COF) of the different components must be developed.

This work, which is linked to T3.1, presents the development of a COF in order to design and size the battery system and power electronics interface in the BESS. This includes the selection of the cell technology based on the different chemistries tested in the project (see D2.1), the selection of the type of modular PE interface (see D1.1), and the sizing of these components. The optimization is performed to find the optimal solution, considering the system cost, lifetime (for the battery and PE systems), and efficiency. The developed framework is modular and adaptable to different applications, also considering different levels of details (optimization from module to pack level or cell to pack level).

The optimization is based on the system architecture and specifications defined in WP1. The battery cell models for different chemistries are provided by WP2. Also, the Energy Management System (EMS) development in WP4 has been considered for the co-design optimization. This is summarized in Figure 1 with the inputs and outputs to/from T3.1.

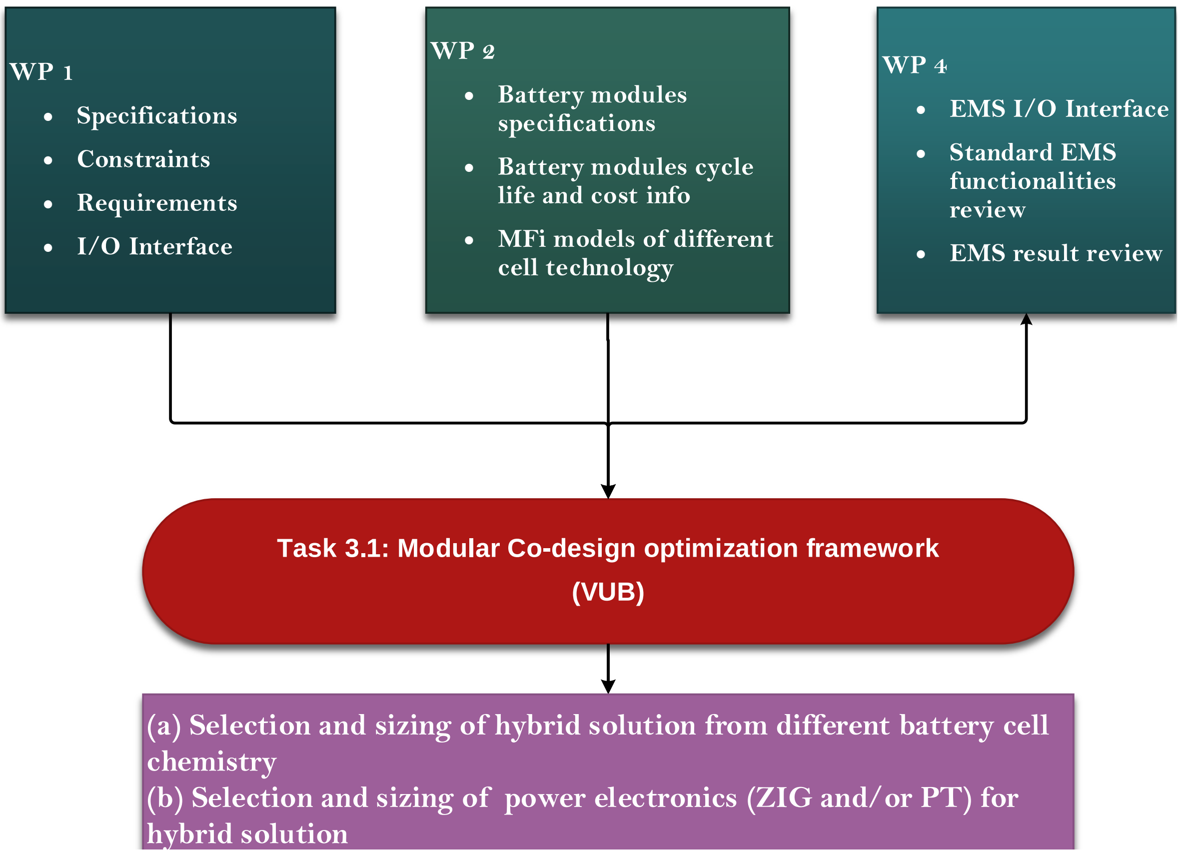

Figure 1. Interaction between Task 3.1 and other WPs (i.e., WP1, WP2 and WP4) and results of Task 3.1

2 System description and components modelling

The HESS and its specifications are described in D1.1 Specification and Requirement, together with the three load profiles that are considered in the project. In this section, the main system architecture and specifications are described in order to be used within the co-design optimization framework. It is worth mentioned that the systems specifications are defined for a prototype-scale solution, but the developed methodology can be equally applied to a full-scale solution.

2.1 HESS description

The system is shown in Figure 2, where a PE interface is used to connect a hybrid battery system to the grid using a universal EMS. The battery system will be composed of two different cell technologies, one acting as a high-energy (HE) battery and the other one as a high-power (HP) battery in order to be used during the peaks of the load profile.

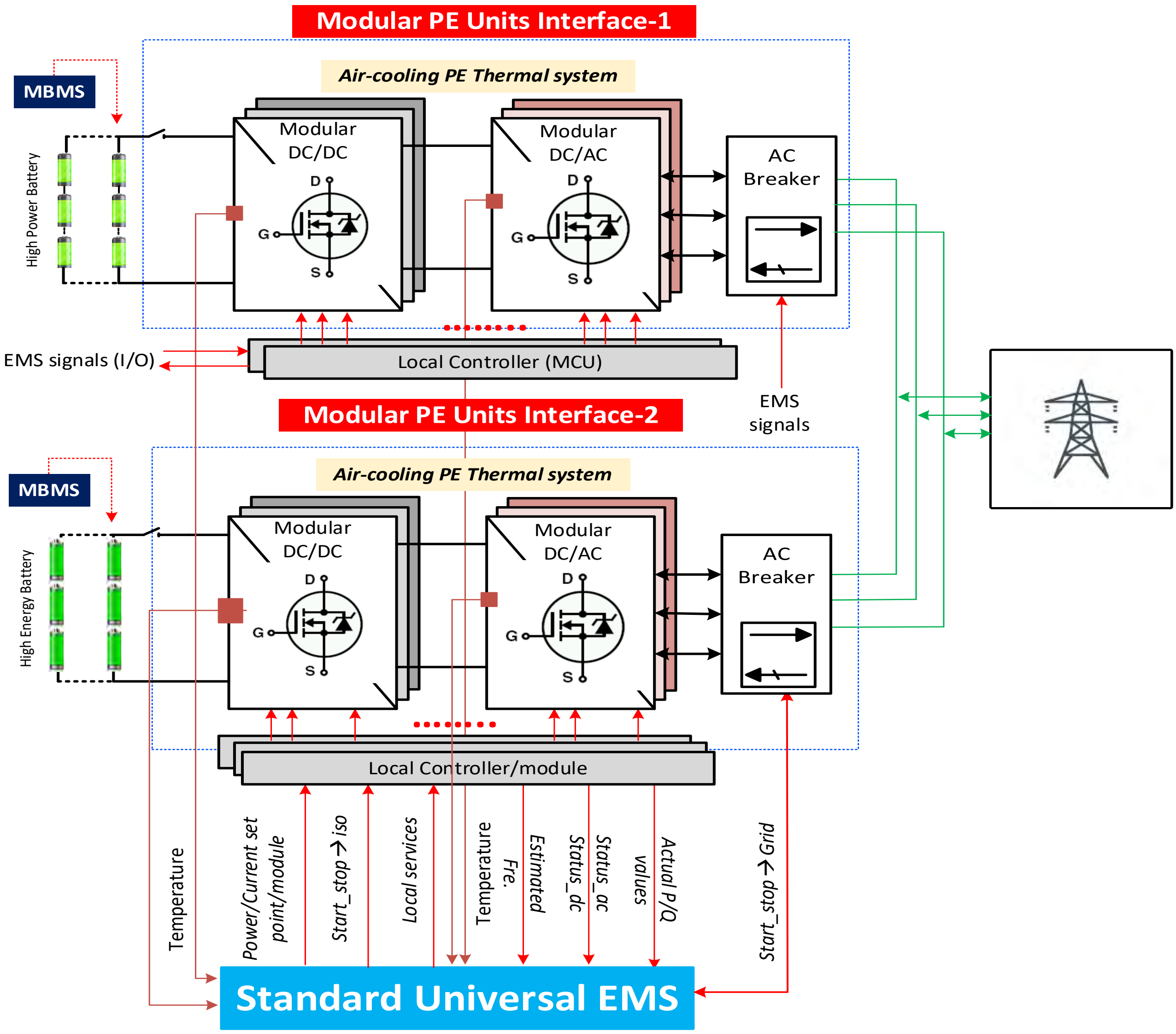

Figure 2. Overall system architecture of the Modular PE interface with both logical (red) and physical (black) interface connectivity (D1.1)

2.2 Battery Model

In order to constitute the hybrid battery system, four cell technologies are considered: NMC, LTO and LFP (1st and 2nd life). These cells have been modelled with medium fidelity, as described in D2.1. The type of model selected is an Electric Equivalent Circuit (EEC) model. It provides the cell voltage as a function of the cell State of Charge (SoC), cell temperature, cell charge and discharge current. It has been implemented in Matlab/Simulink and coupled with a thermal model. In the model, the pack can be configured as a series/parallel combination of modules and a module can be configured as a series/parallel combination of cells.

The cells are electrically interconnected, and their connections are modelled with a resistor in series. The electrothermal cell model described in D2.1 is used for the optimization and implemented in Matlab/Simulink as a battery module. The model inputs are power or current profiles and an ambient temperature profile. Its outputs are module and cell voltages, module and cell power(s), module current, SoC, cell temperatures and cell Joule losses. In this task using these model outputs, the respective efficiency (η) of different battery technologies has been estimated using (1), where P_m and $P_{m.loss}$ represent the output module power and losses, respectively. The absolute value is taken in order to cover both charging and discharging of the battery.

$$\eta_{Bat} = \frac{|\int P_m|}{|\int P_m| + |\int P_{m.loss}|} \tag{1}$$

2.2.1 Battery Cycle Life Estimation

The battery lifetime of each cell chemistry has been estimated considering cyclability using (2) [1]. Even though exact State of Health (SoH) values would be preferred, no aging tests have been performed at this stage of the project. Further SoH modelling will be performed for the selected cells.

$$cycles = \frac{1}{2}\left(\frac{\sum_{t=1}^{T} E_{bat}(t) - E_{bat}(t-1)}{DoD(max) * Bat\_Size}\right) \tag{2}$$

The different cell technologies are either used as HE or HP cells based on their C-rate characteristics. In iSTORMY, the solution relies on optimal hybridization design on the DC side of the system with a combination of different battery packs; and the final solution will be based on a combination of energy modules and power modules to find the optimum level of power and energy of the battery for the desired power profile in each use case. So, the considered cells in this task are categorized as HP modules and HE modules based on cell characteristics, especially C-rate. This is presented in Table 1, where LTO and NMC modules are considered as HP modules because they have a rather high C-rate and low energy capacity while LFP (1st and 2nd life) modules are considered as HE modules because they have high energy capacity and rather low C-rate limits. Although the second-life battery (LFP-A123) has a low energy capacity, it has been classified as a HE one as well in order to improve its remaining useful lifetime by deliberately limiting the C-rate. The characteristics of the different battery modules are represented in Table 1 below, considering that the optimization in iSTORMY is performed at module level, the following information (price, cyclability) will also be considered for specific modules.

From the available information in [2] and CEGASA's experience, the cyclabilities of first-life LTO, NMC, and LFP cells for stationary storage application are presented in Table 1. The cyclability information is presented in the table considering the 80% DoD until the specific capacity of battery reaches 80% of its initial value. It is worth mentioning that these are estimations, due to the lack of information provided by the battery manufacturers and the absence of ageing test results, some inaccuracy is expected. Even though the estimations are limited by the available information, the values presented in Table 1 are estimated using the best of our knowledge and experience. The cyclability of the 2nd life battery, namely A123 cell, has been estimated using the cell datasheet [3]. In the cycle life estimation, the remaining useful life of 2nd life is considered from 91% SoH to 60% SoH. Using Figure 3, 9000 cycles are calculated as a linear reduction of cycle life. However, this number is not a clear representation of a cell life; and achieving right cycle life information, especially for 2nd life cells, is a complex process. 4000 cycles are considered here assuming acceleration of ageing can occur after reaching 80% SoH.

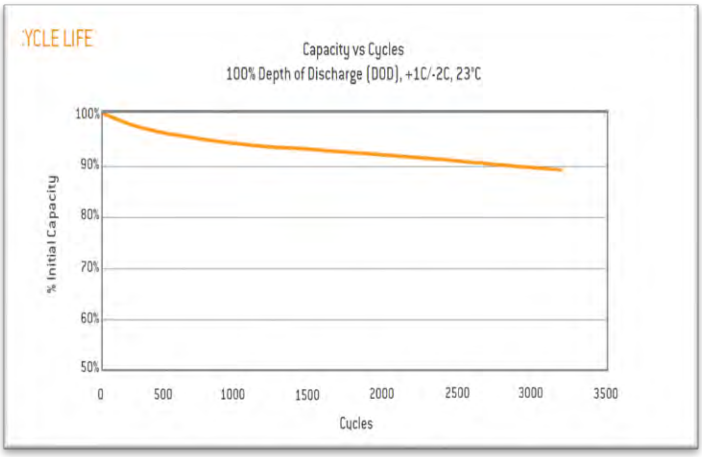

Figure 3. Cycle life characteristics of an A123 cell [3]

2.2.2 Battery cost estimation

The prices of the modules have been considered at this year 2021 in €/kWh in order to have numbers that are as close as possible to reality, based on CEGASA's market experience. Predictions for the upcoming years are very uncertain and will be used in WP5 for an assessment of the overall system expected price evolution. The optimization is here based on more tangible prices, even though the market for second-life modules is still in an early state and there are no clear figures. In particular, the price considered for the second-life battery is selected based on the purchase price in iSTORMY of the A123 cells with 91% SoH remaining. Finally, the price of the MCP is not taken into consideration as it will be nearly equal for the different battery technologies.

Table 1. Battery Module Parameters

Type	Chem.	Config.	Voltage (V)	Capacity (Ah)	C-rate	Cyclelife @80% DoD	Cost (€/kWh) Without MCP @2021
HP	LTO	12s3p	27 V	60 Ah	-2C to +2C [1]	14000	625 €/kWh
HP	NMC	14s1p	51 V	50 Ah	-2C to +2C	1429	250 €/kWh
HE	LFP	15s1p	48 V	280 Ah	-1C to +1C	4530	240 €/kWh
HE	LFP-2	18s1p	58 V	150Ah	-1C to +1C	4530	240 €/kWh
HE	2nd Life (A123)	7s3p	23 V	60 Ah	-2C to +2C	4000	555 €/kWh[2]

[1] The LTO C-rate is limited here due to the lack of test data for higher C-rates; the actual C-rate of the LTO cells is higher than what is noted here.

[2] From the market study, the price for LFP 2nd life battery is around 230 €/kWh; however a higher price is considered here because the small-scale nature of the project, with no economies of scale. Also, the SoH is still 91% compared to lower SoH for regular LFP 2nd life batteries in the market.

2.3 Modular PE interface

As described in D1.1, two different modular PE interfaces will be considered in the optimization for low cost, high efficiency and longer lifetime, from both PE OEMs involved in the project:

- **Interface 1**: Combined DC/DC-DC/AC converters from **OEM1** with isolation within the modules.
- **Interface 2**: Separated DC/DC and DC/AC converters with common DC link from **OEM2** and 50 Hz grid-side transformer for isolation.

The detailed specifications and constraints are described in Section 3 on the design optimization framework.

2.3.1 PE interface topologies

Considering both possible PE interfaces and their characteristics, four PE interface topologies are investigated to connect the hybrid (HE and HP) battery system to the grid:

- **Configuration 1** – Figure 4: The HE and HP battery packs are both connected to the grid using interface 1.
- **Configuration 2** – Figure 5: The HE and HP battery packs are both connected to the grid using interface 2 with a common DC link.
- **Configuration 3** – Figure 6: The HE battery pack is connected to the grid using interface 2 while the HP pack is connected using interface 1.
- **Configuration 4** – Figure 7: The HE battery pack is connected to the grid using interface 1 while the HP pack is connected using interface 2.

Four connection configurations have been made here considering that the power of each battery pack can be controlled separately to meet the grid services and load requests. The modularity of the PE units increases their reliability since the failure of a single PE unit or battery pack does not affect directly the operation of the other one.

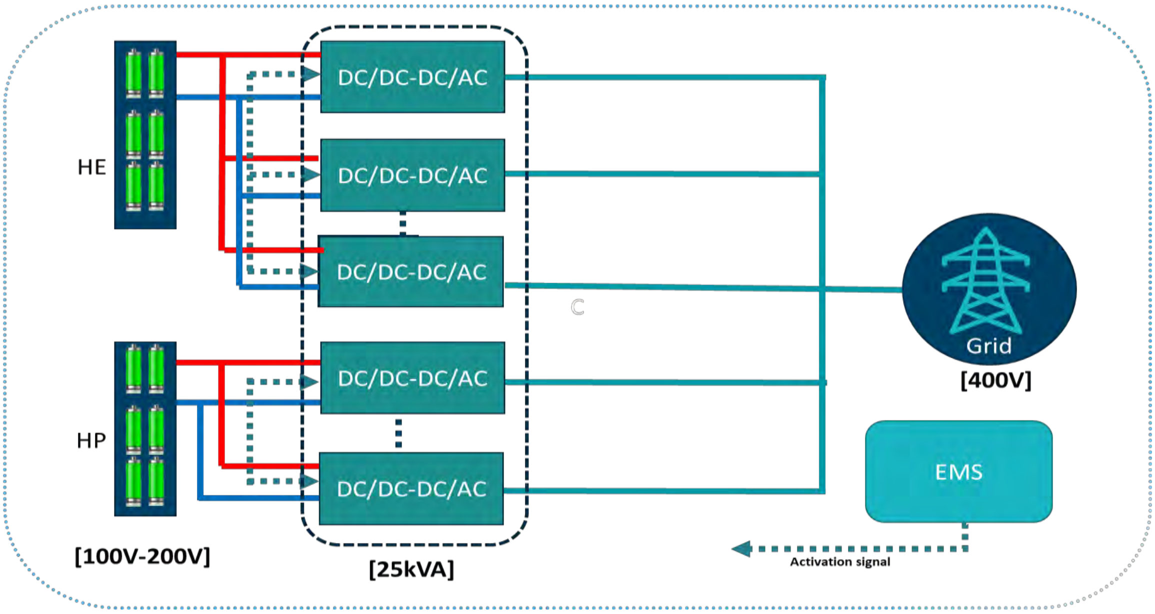

Figure 4. PE configuration 1: interface 1 is used for HE and HP packs

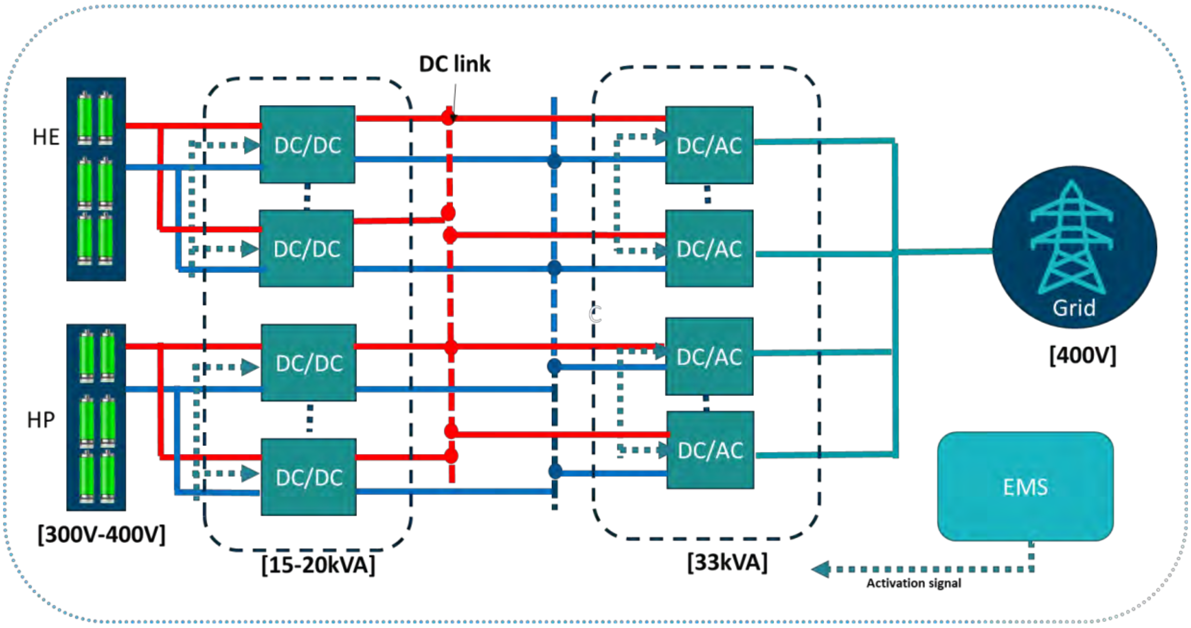

Figure 5. PE configuration 2: interface 2 is used for HE and HP packs

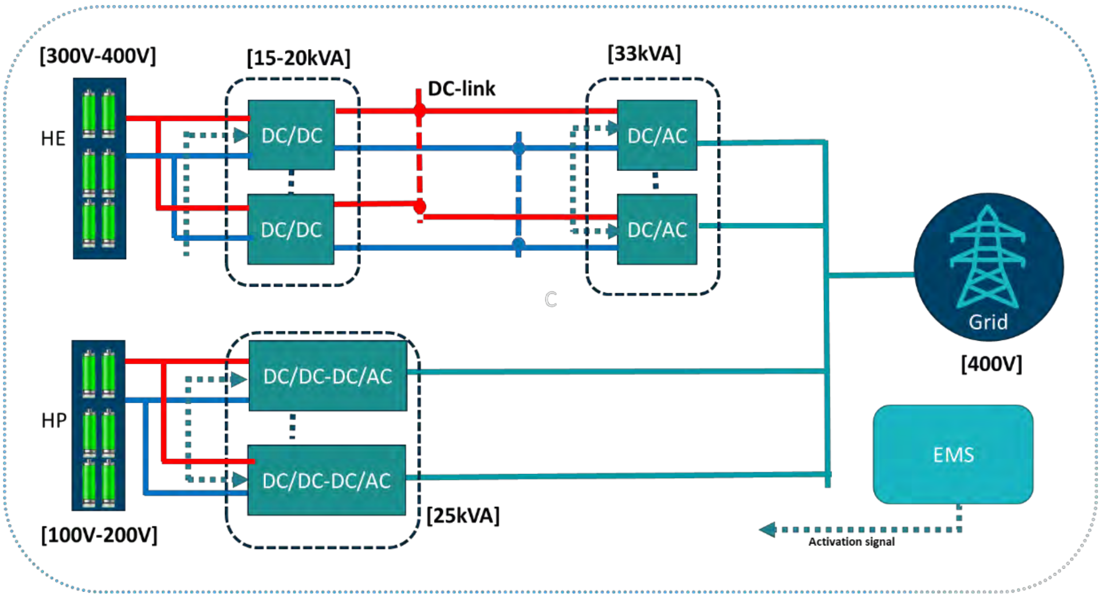

Figure 6. PE configuration 3: interface 2 for HE pack and interface 1 for HP pack

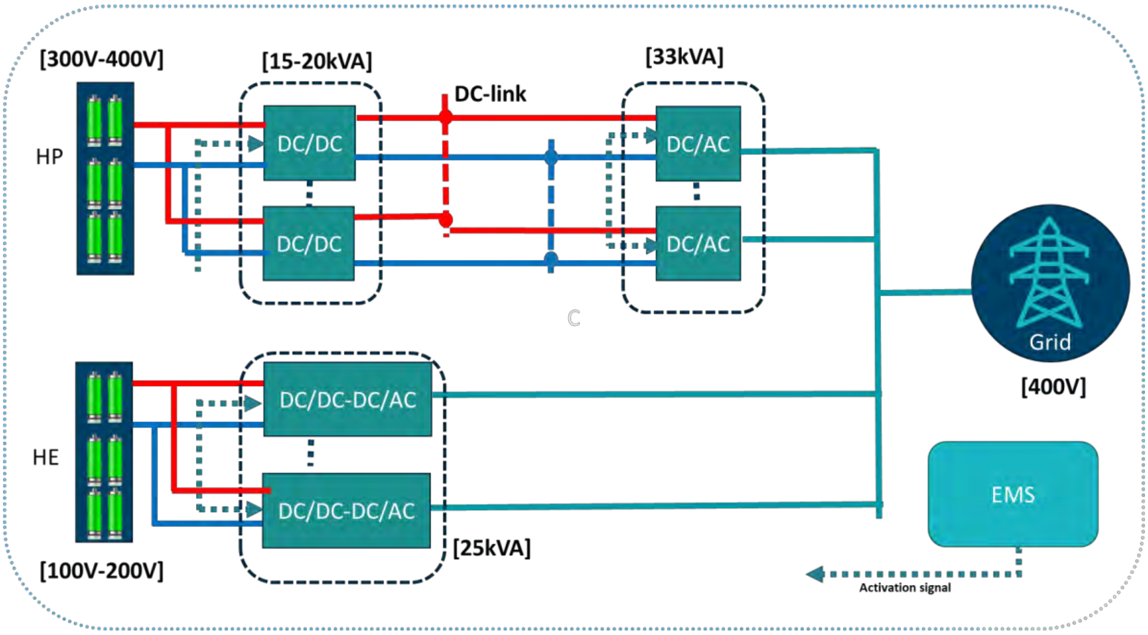

Figure 7. PE configuration 4: interface 1 for HE pack and interface 2 for HP pack

2.3.2 Low-fidelity PE interface modelling

The low-fidelity (LoFi) models for both power electronics interfaces (DC/DC and DC/AC converters) are based on efficiency maps provided by OEM1 and OEM2, in function of the battery voltage, dc link voltage and load power request. The efficiency map for a module from OEM1 used in interface 1 is shown in Figure 8.

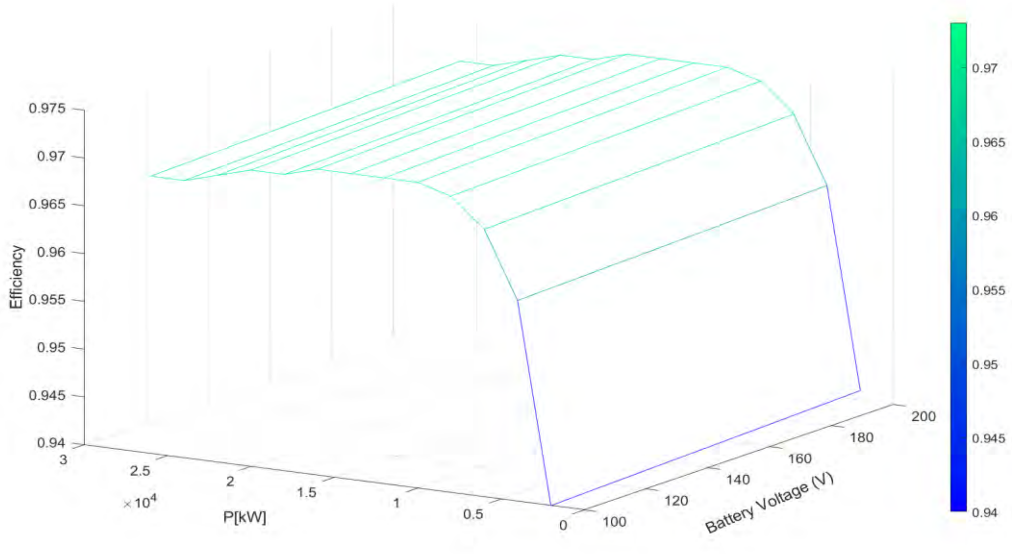

Figure 8. Efficiency map for 1 module from OEM1 comprised of a single stage DC/AC

In PE interface 2, there are two modular stages: DC/DC and DC/AC with a DC link in between. The modular DC/DC and DC/AC LoFi model has been developed based on the efficiency maps in Figure 9 and Figure 10.

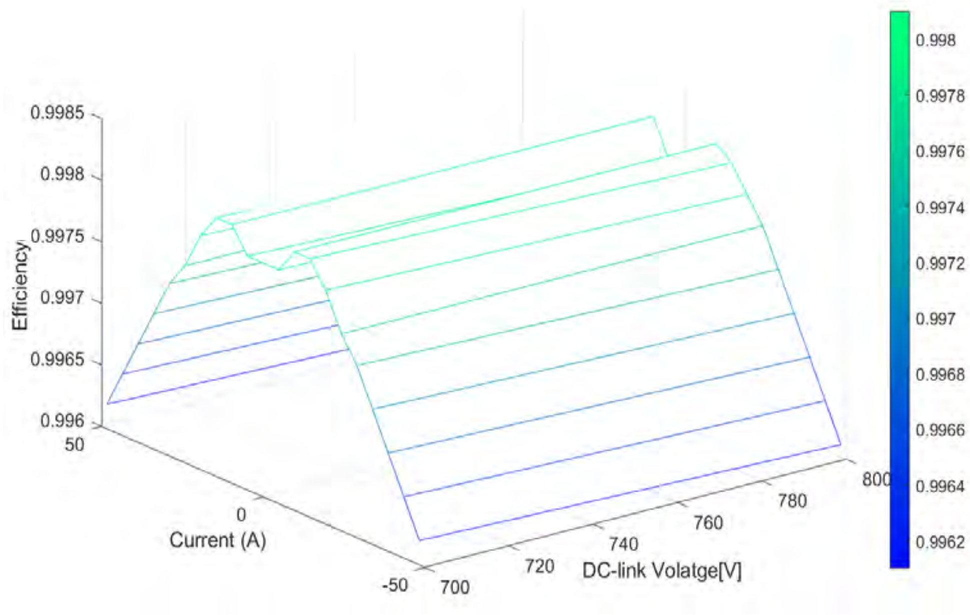

Figure 9. Efficiency map for 1 DC/AC module from OEM2

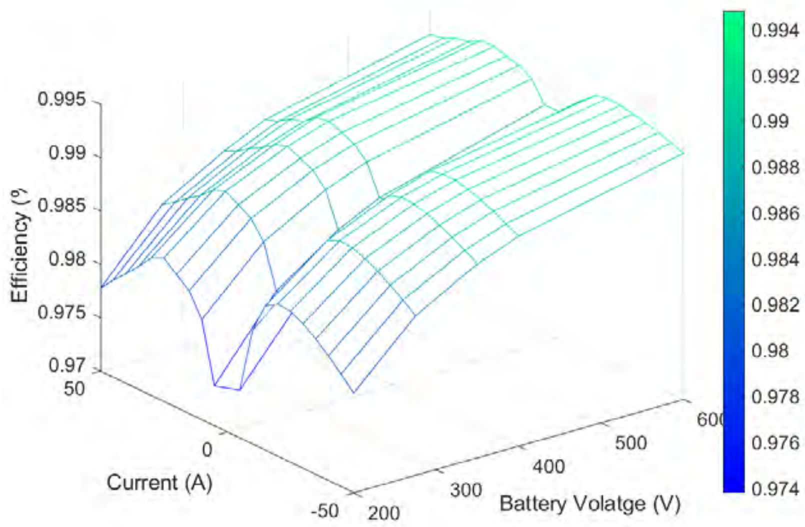

Figure 10. Efficiency map for 1 DC/DC module from OEM2

In order to consider the lifetime of the PE converters in the optimization, the LoFi models are extended with a fast electro-thermal model and analytical reliability assessment. The process from the LoFi PE modelling to the PE lifetime estimation is shown in Figure 11 and is conducted in the following subsections.

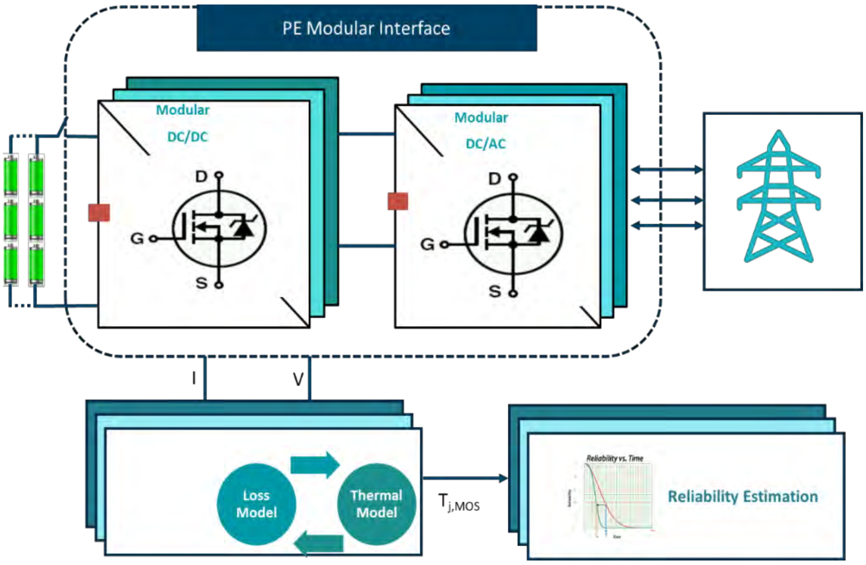

Figure 11. Lifetime estimation process from the LoFi model of the PE interface

2.3.3 PE interface electro-thermal modelling

Power semiconductors and their packaging are subject to several failure mechanisms, such as bond wire lifting and breakage, and solder plate fatigue on the base plate and in the chip soldering. Among these, bond wire related failures are the most prominent cause of power modules failures [4]. These are caused by the thermo-mechanical stress induced by the temperature gradients between the components due to the different materials and power losses [5]. Therefore, the assessment of the MOSFET junction temperature is a good way to start the thermal run out of the PE system. Electro-thermal equations are given in (3-5) [6].

$$R_{tot} = \frac{\gamma}{Q} + \delta \quad (3)$$

$$\Delta T = P_{loss} * R_{tot} \quad (4)$$

$$T_{max} = \Delta T + T_{amb} \quad (5)$$

where R_{tot} is the total thermal resistance, and γ and Q are the coefficients to characterize the thermal resistance. The temperature difference (ΔT) is calculated by multiplying the generated power loss (P_{loss}) in terms of heat and R_{tot}; the maximum temperature (T_{max}) of the electrical component can be derived by the summation of ΔT and the ambient temperature of the system (T_{amb}).

2.3.4 PE interface reliability estimation

This subsection seeks to provide an estimation of the system Mean Time Between Failure (MTBF) to evaluate the potential reliability of the modular PE converter. This will provide information to assist in directing and planning for reliability and related program efforts and identify design features critical to reliability. The reliability prediction method used in this analysis is taken from MIL-HDBK-217F(N1/2) [7]. The Mathematical Model used in determining the converter reliability is known as the series model. This model is based on (6-7), where $R(t)$ is the overall reliability of the converter, t is the elapsed operation time (hr), and λ is the constant failure rate.

$$R(t) = e^{-\lambda t} = e^{-\frac{t}{MTBF}}, \quad (6)$$

$$\lambda = \frac{1}{MTBF} \quad (7)$$

Here the PE reliability is only considered with power semiconductors, which are the most failure prone devices in PE converters [8]. Considering that few data are available for SiC switches, MOSFET devices are considered in this preliminary reliability assessment. Further reliability data will be obtained in the project for SiC devices, enabling a thorough reliability assessment of the converters.

The quality of the part for the converter has been selected as MIL Spec quality, but with a lower π_Q factor since they are sourced commercially. All part reliability model includes the effects of environment stresses through the environment factors, π_E. The Ground, fixed type of environment has been selected for reliability model. Moreover, the temperature response is taken from the thermal analysis for worst ambient temperature (45°C). The maximum range is fixed based on the thermal response of the PE for worst mission profile. If the PE lifetime satisfy during worst condition it is obvious that the lifetime will be way higher for normal conditions. In (8), the lifetime calculation for a MOSFET is presented.

MOSFET lifetime →

$$\lambda_p = \lambda_b \pi_T \pi_Q \pi_E \pi_A \pi_B \quad (8)$$

Where $\pi_T = e^{-\frac{Ea}{k} * \left(\frac{1}{Tj+273} - \frac{1}{298}\right)}$ and k = 8.6173303 * 10^{-5}.

The overall part failure rate, λ_p, of the individual components depends on a combination of various stress factors including λ_b (base failure rate), π_T (temperature factor), π_Q (quality factor), π_A (application factor), π_E (environment factor) and π_B (acceleration voltage breakdown). These are considered for MOSFET lifetime formulation.

As the topology is not defined yet, we considered 2-level 3-phase inverter for (ac/dc) and 3-phase interleaved dc/dc. Hence, six switches in series association are considered for the system-level lifetime. The system-level lifetime formula is given in (9).

System-level lifetime →

$$R(t) = (\, e^{-\lambda t})^6 \quad (9)$$

2.4 EMS development for co-design

Considering the hybridization of the battery pack with two different battery technologies, the requested power has to be distributed between the HE and HP packs. It is necessary to incorporate the EMS in the design optimization framework to ensure that the power distribution follows the battery technological constraints such as temperature, SoC, C-rate, etc. as well as the load profile with positive and negative dynamics. The EMS is developed in parallel with WP4 to enable the co-design optimization, based on the I/O interfaces defined and the standard EMS selected. The universal EMS will be further developed in WP4 for improved performance, reliability and lifetime.

A hybrid control strategy has been considered, as shown in Figure 12. Generally, among the rule-based EMS approaches, either deterministic or filtering based control strategies are mostly used because of their simplicity and ease of implementation [9]. Here, the combination of both has been considered to follow the load dynamics and battery constraints in terms of lifetime.

This power split between HE and HP batteries has been developed in parallel and in collaboration with the initial work in Task 4.1 on the universal EMS. An initial power split is considered here using (10-11) [10], where P_{HP} is the power of the HP battery [W], P_{HE} is the power of the HE battery [W], $P_{requested}$ is the requested power from the load profile [W] and τ is the time constant of the filter [s].

$$P_{HE} = \frac{P_{requested}}{\tau \cdot s + 1} \tag{10}$$

$$P_{HP} = P_{requested} - P_{HE} \tag{11}$$

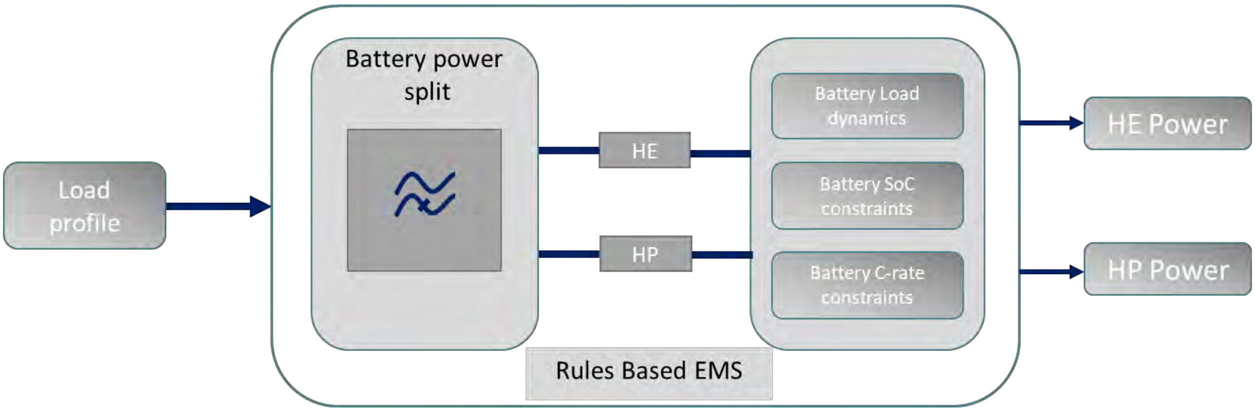

Figure 12. Energy management strategy considered in the optimization framework

The system requirements have been defined in D1.1 and will be further indicated in Section 3 but the load profile considered as input to the EMS also has an influence on the batteries and PE interface performance and selection. Figure 13 shows the load profile dynamics from use case 2 (see D1.1), which is considered in this co-design optimization framework for the power sharing between HE and HP batteries. One of the main reasons for choosing this use case as a basis for the co-design optimization is that the power profile is quite demanding both in terms of the required instantaneous power and the requested energy to restore the SoC. The maximum power requested from the system is close to 90 kW, in order to have the final solution sized around 100 kW. Since the final solution will be optimised for this demanding profile, it is expected that the chosen battery technologies and PE interface configurations will also be suitable for other use cases. It should be also highlighted that the high modularity and interoperability of the solution will be easily adjustable to other applications even with different system configurations.

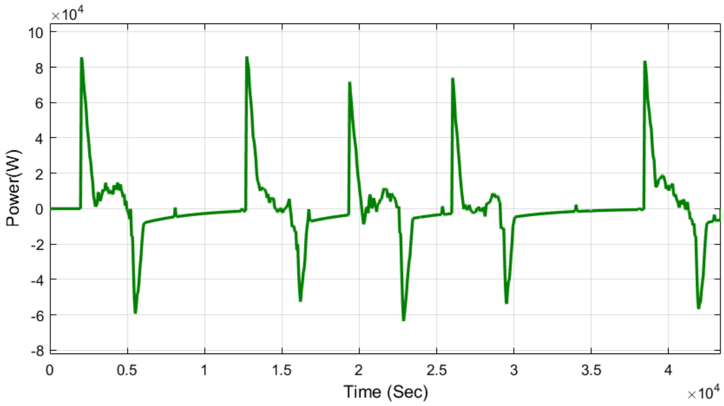

Figure 13. Use case-2 load profile

3 Co-design Optimization framework

Overall, the co-design optimization framework aims at selecting the cell technologies to be used, determining the configuration of the HE and HP battery packs (number of modules in series and parallel, i.e. battery capacity), the type of power electronics interface that will be used for each battery pack and the number of converters used. This section details the development of the optimization framework, based on the information gathered in the previous sections.

3.1 Optimization framework description and selection

iSTORMY requires an optimal configuration of hybrid battery pack solution in combination with power electronics interface for a longer lifetime and lower cost. In addition to battery and PE interfaces selection, configuration and size, the right dc link voltage must be obtained as well. A nested EMS is also used to make sure the system is optimally sized in terms of longer lifetime and higher efficiency, enabling the co-design optimization. The framework architecture is shown in Figure 14; it is built in a modular fashion with input and programming layers. The input layer deals with the input data required for the system design from the user. The programming layer interfaces the input data and the component model with a specific system model configuration to final output with iterative optimization routine and decision maker criterion. The routine incorporates a multi-objective optimization with Evolutionary optimizer which identifies the Pareto front or feasible solution that satisfies all the requirements.

In the framework, a multi-objective function has been considered rather than having a straight single outcome from a single objective so that more insight can be achieved from individual component perspective and can be discussed based on the consortium's expertise, to select the right solution for iSTORMY.

3.1.1 Problem formulation

A generic multi-objective problem can be formulated as in (12).

$$Minimize\ F(x) = [f_1(x), f_2(x), f_3(x), f_4(x)]$$

Subject to: $g_i(x) \leq 0$

$$X = \{x | g_m(x) \leq 0, m = 1,2,3, \ldots . M\} \qquad (12)$$

$$S = \{F(x | x \in X)\}$$

where x is the vector of design variables; $g_i(x)$ is the inequality constraints vector and m is the number of inequality constrains; X denotes the feasible decision space and S is the criterion space. In the iSTORMY optimization, objective functions need to be either maximized or minimized; the ones to maximize will be reflected to be minimized. Also, the vector x contains the number modules in series and in parallel for the HE and HP batteries, the DC link voltage for PE interface 2, all PE interface converters ratings, the capacity of the battery packs, their SoC and their C rates. The problem is also formulated as a mixed-integer problem where battery modules numbers are discrete and other design variables are continuous.

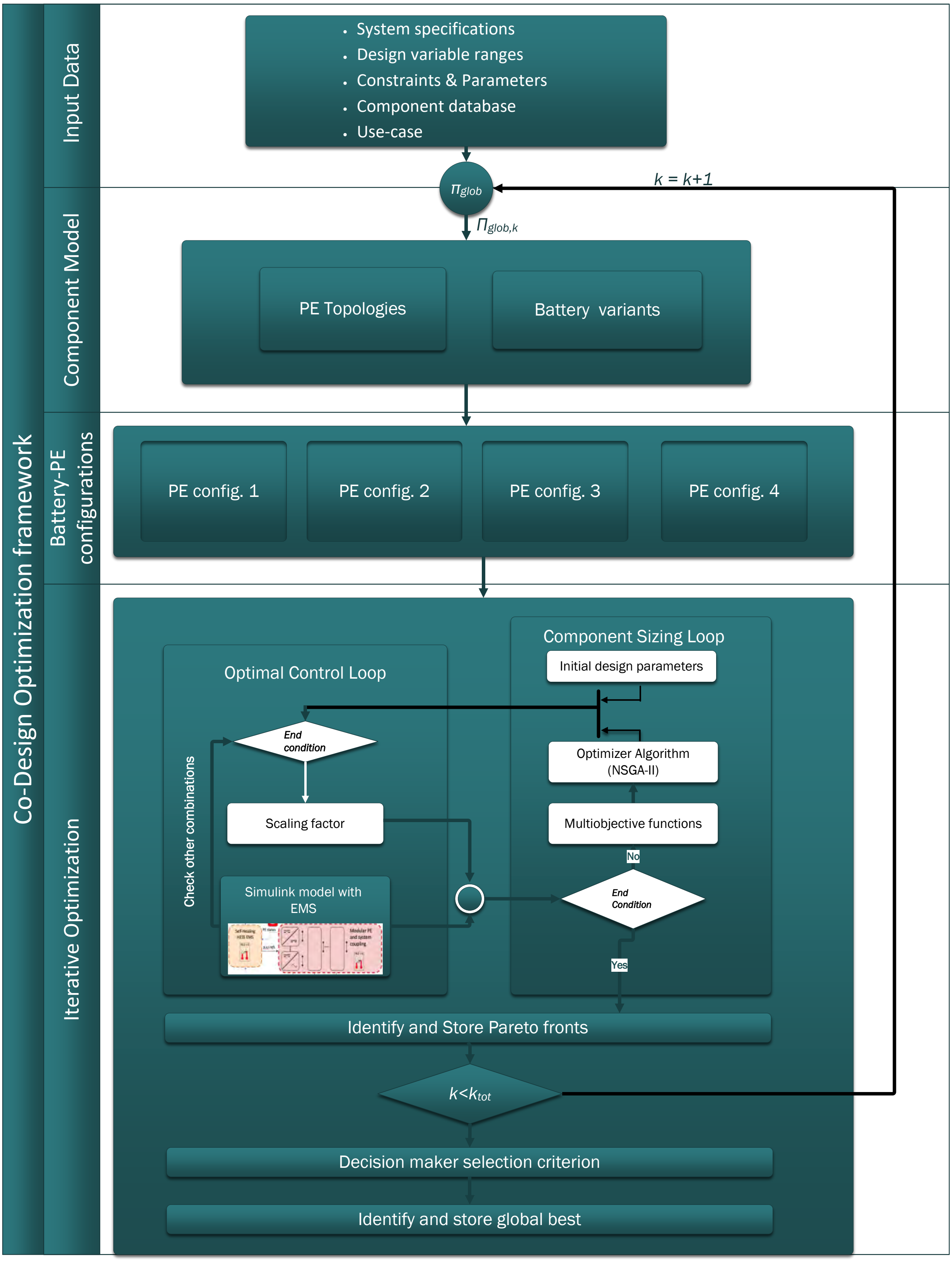

Figure 14. Co-design optimization framework architecture

3.1.2 Objective function

The objective functions that are used in the framework are prepared in a structure so that combination of different battery and PE configurations can be evaluated in the same fashion. These objective functions are the system cost over 10 years (f_1), system efficiency (f_2), lifetime of the battery packs (f_3) and lifetime of the PE interfaces (f_4).

In the cost objective function, capital investment (CAPEX) and operating (OPEX) costs, also considering system losses, are taken into account in order to reach the Total Cost of Ownership (TCO) over a certain period of time. The TCO is the summation of CAPEX and OPEX and here considered over 10 years of service lifetime [11], in order to consider the influence of the system operation for a standard stationary electric energy storage system lifetime. The residual value of the system will be considered in the LCOS. The CAPEX is calculated using (13). In the CAPEX only power electronics and battery costs have been considered as they have a direct impact on the system design optimization outcome.

$$CAPEX = (C_{PE1} \times P_{m.PE1} \times \mathrm{N_{PE1}} + C_{PE2} \times P_{m.PE2} \times \mathrm{N_{PE2}}) + (C_{BAT} \times \mathrm{E_{BAT1}} + C_{BAT2} \times \mathrm{E_{BAT2}}) \quad (13)$$

where C_{PE1}, C_{PE2} are the costs of PE interfaces for HE and HP batteries, respectively [€/kW]; $P_{m.PE1}$, $P_{m.PE2}$ are the modules rated power of the PE interfaces [kW]; $\mathrm{N_{PE1}}$, $\mathrm{N_{PE2}}$ are the numbers of modules of the PE interfaces; C_{BAT}, C_{BAT2} are HE and HP battery costs, respectively [€/kWh] and $\mathrm{E_{BAT1}}$, $\mathrm{E_{BAT2}}$ are the capacities of the HE and HP batteries, respectively [kWh].

The OPEX is calculated using (14). In the OPEX, the potential battery replacement cost during the 10 years of operation has been taken into account where 8% annual reduction of battery price has been considered during replacement with respect to present battery price in this task until 2030.

$$OPEX = \sum_{\mathrm{y=1}}^{\mathrm{y=10\ yrs}} \left(\mathrm{E_{tariff}} \times \mathrm{E_{tot\_req}} \times \eta_{sys} + replacement.cost\right) \quad (14)$$

$$f_1 = TCO = CAPEX + OPEX$$

where $\mathrm{E_{tariff}}$ is the energy tariff of EU-27 in 2019 and amounts to 0,13€/kWh [12], $\mathrm{E_{tot\_req}}$ is the total energy request in [kWh], $\eta_{\mathrm{PE.B1}}$,$\eta_{\mathrm{PE.B2}}$ are the efficiencies of the PE interfaces connected to HE battery and HP battery, respectively; η_{B1}, η_{B2} are the efficiencies of HE battery pack and HP battery pack, respectively; and $replacement.cost$ is the replacement cost in [€].

The efficiency of the HESS is estimated based on the efficiency of the two independent battery packs and their connected PE interfaces. The system efficiency is calculated as in (15).

$$f_2 = \eta_{sys} = \frac{(\eta_{\mathrm{PE.B1}} \cdot \eta_{\mathrm{B1}} + \eta_{\mathrm{PE.B2}} \cdot \eta_{\mathrm{B2}})}{2} \quad (15)$$

The lifetime of each battery and PE modules of different topologies have been estimated using (16-18), as discussed in Section 2. In this task 365 days have been considered for operation within one year. The objective is to maximize the lifetime of both the battery packs (f_3) and the PE interfaces (f_4).

$$f_3 = Bat_{lifetime} = \mathrm{cyclelife}/(\mathrm{cycle} \times \mathrm{operating\ days}) \quad (16)$$

$$cycle = \frac{1}{2}\left(\frac{\sum_{t=1}^{T} E_{bat}(t) - E_{bat}(t-1)}{DoD(max) * Bat\_Size}\right) \quad (17)$$

$$f_4 = R(t) = (\, e^{-\lambda t})^6 \quad (18)$$

3.1.3 Constraints

The constraints of the optimization problem are defined by the sizing and selection requirements such as the number modules for configuring each battery pack, number of power electronics modules and their power rating. Table 2 and Table 3 present/summarize the explicit constraint/variables defined in D1.1 and further specified by the OEMs for both PE interfaces 1 and 2. The battery packs will be sized to be close to 100kW and 100kWh with an upper margin of 15%.

Table 2. Specification and constraints for PE interface 1

Constraints/variables	Description	Specifications
$idx_{bat} \in [1, 2 \ldots \mathrm{n}]$	N variants of Battery types	▪ Max current per module 200A ▪ Power rating per module: 25kW ▪ Total Power rating: <125kW
$idx_{ACDC} \in [1, 2, 3 \ldots \mathrm{n}]$	N variants of DC/AC module combinations	
$100 \leq Batt_{voltage} \leq 200$	Battery voltage range	
PE stage efficiency ≥ 98%*98%	Power electronics efficiency input to output, half to full power	

Table 3. Specifications and constraints for PE interface 2

Constraints/variables	Description	Specifications
$idx_{bat} \in [1, 2 \ldots \mathrm{n}]$	N variants of Battery types	▪ Total Power rating: <125kW ▪ Power rating per module (DC/AC): 33kVA ▪ Power rating per module (DC/DC): 15kW-20kW ▪ Max current per module (DC/DC) 50A
$idx_{DCDC} \in [1, 2, 3 \ldots \mathrm{n}]$	N variants of DC/DC converter combinations	
$idx_{ACDC} \in [1, 2, 3 \ldots \mathrm{n}]$	N variants of DC/AC converter modularity	
$700V \leq V_{DClink} \leq 800\mathrm{V}$	DC-Link voltage range	
$300 \leq Batt_{voltage} \leq 400$	Battery voltage range	
PE stage efficiency ≥ 98%*98%	Power electronics efficiency input to output, half to full power	

3.1.4 Optimizer Selection

The optimization of the HESS is a complex and non-convex problem. Therefore, to keep the flexibility in decision-making without giving complete control to the algorithm to decide the final result, NSGA-II is considered in the task as NSGA-II uses a Pareto-front hierarchy and adopts an elitism mechanism to retain the best solutions generated during the search [13]. Besides, by nature, Genetic Algorithms (GAs) perform an efficient and parallelizable search. A similar characteristics system optimization problem has also been performed with the adopted algorithm [14], [15] for its capacity of evolving solutions with multi-objective functions with discrete and continuous design variables. For iterative optimization run the optimizer is set with the following settings:

- Population size: 100
- Number of generations: 15
- Stall generation limit: 50

3.1.5 Selection criterion

When a number of Pareto optimal solutions are found after one successful complete iterative optimization routine then to find the best solution among all feasible solutions, a composite function in (19) is applied with different weighting factors for each objective based on their importance in the final HESS solution. The weighted sum of the various objective functions is given by:

$$O_{ws}(\mathrm{x}) = \sum_{i=1}^{k} w_i f_i(x) \tag{19}$$

where $w_i \in [0,1]$ are the weight factors assigned to each objective and $f_i(x)$ is normalized to [0,1], resulting in a dimensionless number. In this task the solution selection criterion is set as in (20):

$$S = 0.6 \cdot f_1(x) + 0.1 \cdot f_2(x) + 0.2 \cdot f_3(x) + 0.1 \cdot f_4(x) \tag{20}$$

where f_1, f_2, f_3 and f_4 denote TCO over 10 years, system efficiency, battery lifetime and PE lifetime, respectively.

4 Optimization framework results

As mentioned previously, the optimization for the battery system has been here performed from module to pack level, even though the optimization framework is able to further optimize the system configuration from cell to pack level. This is due to the fact that the production cost of new modules, including early design etc. would be much higher. The considered selection criterion gives a weight of 60% for the TCO over 10 years, 10% for the efficiency, 20% for the battery system lifetime and 10% for the PE interface lifetime.

The optimization is performed for each combination of PE interfaces and HE/HP battery types, which totals to 24 combinations as Table 4 where the optimal solution is obtained. Within this set of solutions, the few best ones in terms of objective function will be considered for implementation and discussed to reach the final iSTORMY solution. First, an example is given of how the solution is obtained for one specific combination.

Table 4. Combination of battery and PE interfaces (PE interface 1 – PE-1; PE interface 2 – PE-2)

PE Configuration 1		PE Configuration-2		PE Configuration-3		PE Configuration-4	
LTO	PE-1	LTO	PE-2	LTO	PE-2	LTO	PE-1
LFP	PE-1	LFP	PE-2	LFP	PE-1	LFP	PE-2
Combination-1		**Combination-7**		**Combination-13**		**Combination-19**	
NMC	PE-1	NMC	PE-2	NMC	PE-2	NMC	PE-1
LFP	PE-1	LFP	PE-2	LFP	PE-1	LFP	PE-2
Combination-2		**Combination-8**		**Combination-14**		**Combination-20**	
LTO	PE-1	LTO	PE-2	LTO	PE-2	LTO	PE-1
2nd life	PE-1	2nd life	PE-2	2nd life	PE-1	2nd life	PE-2
Combination-3		**Combination-9**		**Combination-15**		**Combination-21**	
NMC	PE-1	NMC	PE-2	NMC	PE-2	NMC	PE-1
2nd life	PE-1	2nd life	PE-2	2nd life	PE-1	2nd life	PE-2
Combination-4		**Combination-10**		**Combination-16**		**Combination-22**	
NMC	PE-1	NMC	PE-2	NMC	PE-2	NMC	PE-1
LFP-2	PE-1	LFP-2	PE-2	LFP-2	PE-1	LFP-2	PE-2
Combination-5		**Combination-11**		**Combination-17**		**Combination-23**	
NMC	PE-1	NMC	PE-2	NMC	PE-2	NMC	PE-1
LFP-2	PE-1	LFP-2	PE-2	LFP-2	PE-1	LFP-2	PE-2
Combination-6		**Combination-12**		**Combination-18**		**Combination-24**	

4.1 Optimal solution for a specific combination

The example here considers the HE battery as LFP and the HP battery as LTO, with PE configuration 1 (i.e. PE interface 1 to connect them both to the grid). The 3-dimensional optimization with the possible resulting solutions in shown in Figure 15 considering TCO, efficiency and lifetime. The optimization selects the optimal solution within these, as shown in RED in the figure.

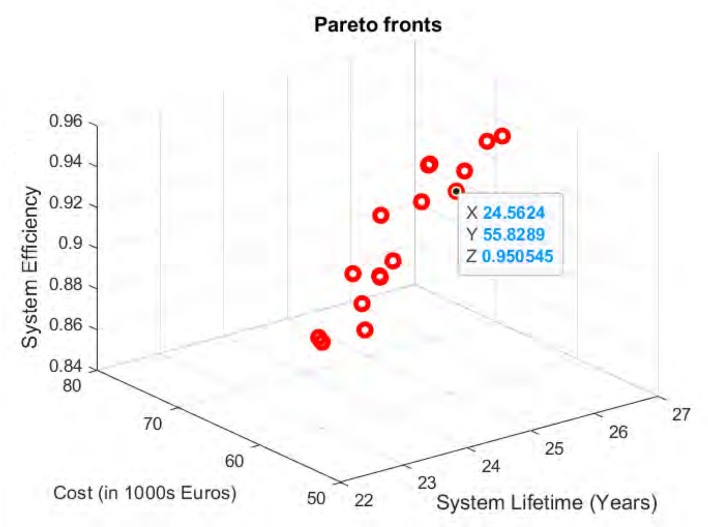

Figure 15. Feasible solutions with LFP and LTO cells connected with PE interface 1

Each of the solutions meets the constraints defined in the previous sections. The resulting configuration is shown in Table 5. This is done for each of the 24 possible combinations and the comparison of the optimal solutions is done in the next subsections.

Table 5. Example of resulting configuration for LFP and LTO battery combination with PE configuration 1

Combination	Chemistry	Module Configuration	Battery Voltage Nom. (V)	Energy (kWh)	System Lifetime (Years)	PE Interface-1		System Efficiency (%)	TCO in 10yrs (€)
						Module rating (kVA)	No. of modules		
5	LTO	5s6p	135	48,6	24,5	25	3	95	55.828
	LFP2	3s2p	174	52,2			1		

4.2 Optimal solutions for each combination

The 24 optimal solutions for all PE interface configurations and battery technologies combinations are shown in Table 6 to Table 9 below, with the indication of system lifetime (indicative combination of battery and PE interface lifetime), system efficiency and system TCO over 10 years.

Table 6. Optimal solutions from each battery combinations for PE configuration 1

Combination	Chemistry	Module Configuration	Battery Voltage Nom. (V)	Energy (kWh)	System Lifetime (Years)	PE Interface-1		System Efficiency (%)	TCO in 10yrs (€)
						Module rating (kVA)	No. of modules		
1	LTO	6s5p	162	48,6	24	25	2	95	56.091
	LFP	4s1p	192	53,7			2		
2	NMC	3s6p	153	45,9	15	25	2	94	53.644
	LFP	4s1p	192	53,7			2		
3	LTO	6s5p	162	48,6	25	25	3	95	73.467
	2nd life	8s5p	184	55,2			1		
4	NMC	3s6p	153	45,9	17	25	3	94,7	80.966
	2nd life	8s6p	184	55,2			1		
5	LTO	5s6p	135	48,6	24,5	25	3	95	55.828
	LFP2	3s2p	174	52,2			1		
6	NMC	3s7p	153	53,55	17	25	2	94	57.788
	LFP2	3s2p	174	52,2			2		

Table 7. Optimal solutions from each battery combinations for PE configuration 2

Combination	Chemistry	Module Configuration	Battery Voltage Nom. (V)	Energy (kWh)	System Lifetime (Years)	PE Interface-2					System Efficiency (%)	TCO in 10 years (€)
						Module (AC-DC)	Module (DC-DC)	Vdclink (V)	AC-DC Rating (kVA)	DC-DC rating (kVA)		
7	LTO	12s1p	324	19,44	20	3	2	760	33	17	91	50.058
	LFP	7s1p	336	94,08			4					
8	NMC	6s1p	306	15,3	14,5	3	1	730	33	16,35	92	49.462
	LFP	7s1p	336	94,08			5					
9	LTO	13s2p	351	42,12	22	3	4	730	33	16,6	97	70.885
	2nd Life	14s3p	322	57,96			2					
10	NMC	6s3p	306	45,9	16	3	5	740	33	15,5	95	73.502
	2nd Life	14s3p	322	57,96			2					
11	LTO	12s3p	324	58,32	24	3	5	740	33	17	96	60.378
	LFP	6s1p	348	52,2			1					
12	NMC	7s3p	357	53,55	17	3	5	770	33	18,35	97	57.513
	LFP	6s1p	348	52,2			1					

Table 8. Optimal solutions from each battery combinations for PE configuration 3

Combination	Chemistry	Module Configuration	Battery Voltage Nom. (V)	Energy (kWh)	PE Interface-2					PE Interface-1		System Lifetime (Years)	System Efficiency (%)	TCO in 10 years (€)
					(AC/DC) No.	(DC/DC) No.	Power AC-DC (kVA)	Vdclink (V)	Power DC-DC (kVA)	No. of modules	Power rating (kVA)			
13	LTO	13s3p	351	63,18	3	5	33	750	17,7	-	-	23	93	64.446
	LFP	3s1p	144	40,32	-	-	-	-	-	1	25			
14	NMC	6s4p	306	61,2	3	5	33	750	16,3	-	-	14.7	91	60.472
	LFP	3s1p	144	40,32	-	-	-	-	-	1	25			
15	LTO	13s2p	351	42,12	2	4	33	720	16,7	-	-	20	94	71.272
	2nd life	7s6p	161	57,96	-	-	-	-	-	1	25			
16	NMC	7s4p	306	71,4	3	5	33	760	18,5	-	-	19,6	94,8	61.545
	2nd life	6s4p	138	33,12	-	-	-	-	-	1	25			
17	LTO	12s3p	324	58,32	2	4	33	730	16,3	-	-	23,6	95	60.912
	LFP2	3s2p	174	52,2	-	-	-	-	-	1	25			
18	NMC	7s3p	357	53,55	2	4	33	770	17,5	-	-	16	95,7	56.299
	LFP2	3s2p	174	52,2	-	-	-	-	-	1	25			

Table 9. Optimal solutions from each battery combinations for PE configuration 4

Combination	Chemistry	Module Configuration	Battery Voltage Nom. (V)	Energy (kWh	PE Interface-2					PE Interface-1		System Lifetime (Years)	System Efficiency (%)	TCO in 10 years (€)
					AC-DC No.	DC-DC No.	Power AC-DC (kVA)	Vdclink (V)	Power DC-DC (kVA)	No. of modules	Power rating (kVA)			
19	LTO	5s2p	135	16.2	-	-	-	-	-	1	25	21	91,6	48.843
	LFP	7s1p	336	94	2	5	33	720	17,5	-	-			
20	NMC	2s4p	102	10,2	-	-	-	-	-	1	25	14,3	90,4	52.097
	LFP	7s1p	336	94	3	5	33	720	16	-	-			
21	LTO	6s5p	162	48,6	-	-	-	-	-	3	25	23	96	74.254
	2nd Life	14s3p	322	57,9	1	1	33	720	19,2	-	-			
22	NMC	3s8p	153	61,2	-	-	-	-	-	4	25	17	96,2	70.357
	2nd Life	14s2p	322	38,6	1	1	33	720	19,1	-	-			
23	LTO	6s5p	162	48,6	-	-	-	-	-	3	25	23,4	96	54.370
	LFP2	6s1p	348	52,2	1	1	33	770	17	-	-			
24	NMC	3s7p	153	53,5	-	-	-	-	-	3	25	18,2	96	58.290
	LFP2	6s1p	348	52,2	1	2	33	730	16,5	-	-			

The details on the lifetime of the different system components are shown in Table 10 for the PE configuration 4. It can be noticed that the NMC modules have a limited lifetime due to their lower cyclability. The lifetime of the PE interfaces is around 18 years and there is few influence from the battery type.

Table 10. Details of the lifetime of each system component for PE configuration 4

Combination	Battery chemistry	Battery Lifetime (Years)	PE interrace 1 Lifetime (Years)	PE Interface 2 Lifetime (Years)	
				AC/DC Module	DC/DC Module
19	LTO	34,3	17,9	14,7	18,7
	LFP	18,8			
20	NMC	1,8	17,9	14,7	18,9
	LFP	18,2			
21	LTO	34,4	18,1	17,2	18,5
	2nd-life	31,1			
22	NMC	3,7	18,1	17,3	18,5
	2nd-life	29,1			
23	LTO	34,1	18,1	17,2	18,8
	LFP2	31,4			
24	NMC	3,5	18	17,2	18,9
	LFP2	33,5			

4.3 Comparison of optimal solutions

The solutions for each combination are here compared in terms of different selection criteria in order to select the best one to be applied in iSTORMY. However, it is also important to take into consideration practical constraints and use common sense, based on the theoretical results obtained from the optimization. This is why a set of "good" solutions is selected for the different criteria in order to lead to the final selection.

Table 11 presents the weighted value of selection criterion 1 (0,6 f_1 + 0,1 f_2 + 0,2 f_3 + 0,1 f_4). The "good" solutions with a weighted value below 0,8 are marked in orange, blue and green.

The results show that the use of 2nd-life batteries is not a feasible solution at this stage due to high prices and little information and data on the battery packs. However, the market will become more mature in the future with higher supply, more data available and lower prices. Today the price of a standard 2nd-life battery pack can be close to 230 €/kWh while it could drop to 80 €/kWh in 2030 in the worst-case scenario [16]. It is therefore likely to become a viable solution to consider in the battery type selection and could even help lower the system cost of storage. However, it is not selected here as the optimization is performed based on more tangible information available at this time.

According to Table 11, it can be seen that the combination of LFP (HE) and LTO (HP) modules is the optimal one. However, there is currently only one supplier providing quality LTO cells on the market and the supply is quite low. Therefore, it is not feasible to consider this type of cell for testing and prototyping in the frame of the project.

Also, only low-fidelity modelling has been used for the PE interfaces in this co-design optimization which can also cause slight variations in the results. Therefore, the consortium believes that with close values for the objective function, a combination of both interfaces is most suited to be implemented in the system to go with higher-fidelity and Digital Twin modelling and enable more extensive research, which discards the "good" solutions with NMC + LFP cells.

Table 11. Weighted value of the selection criterion (0,6 f_1 + 0,1 f_2 + 0,2 f_3 + 0,1 f_4) for each combination

PE configuration	1	2	3	4
LTO + LFP	0,7338	0,7448	0,8200	0,7260
NMC + LFP	0,7576	0,7492	0,8402	0,7861
LTO + 2nd -life	0,8591	0,8296	0,8707	0,8615
NMC + 2nd -life	0,9458	0,8908	0,7738	0,8953
LTO + LFP-2	0,7301	0,7551	0,7709	0,7106
NMC + LFP-2	0,7813	0,7480	0,7595	0,7599

Finally, two solutions remain with the combination of NMC + LFP-2 battery modules. Considering the results in

Table 8, the PE configuration 4 with a combination of both interfaces from OEM1 and OEM2 results in only 1 module for the HE interface, with no modularity. In order to enable modularity in the system and further lifetime and reliability optimization through the development of the EMS in WP4, the solution with NMC + LFP2 and PE configuration 4 seems preferrable.

It should also be mentioned that the definition of the objective function has a non-negligible influence. The selection criterion is defined arbitrarily based on the consortium expertise, but it is interesting to observe the results with slight variations. These are shown in Table 12 (selection criterion 0,5 f_1 + 0,1 f_2 + 0,3 f_3 + 0,1 f_4) and Table 13 (selection criterion 0,7 f_1 + 0,05 f_2 + 0,2 f_3 + 0,05 f_4) where it can be seen that the set of “good” solutions remains similar, with small variations in the ranking. Finally, the estimation for the cyclability of the different cell technologies in Table 1 can also influence the results.

Table 12. Weighted value of the selection criterion (0,5 f_1 + 0,1 f_2 + 0,3 f_3 + 0,1 f_4) for each combination

PE configuration	1	2	3	4
LTO + LFP	0,7532	0,7763	0,8303	0,7579
NMC + LFP	0,7905	0,7878	0,8650	0,8217
LTO +2nd -life	0,8558	0,8331	0,876	0,8596
NMC + 2nd -life	0,9426	0,8981	0,7857	0,9052
LTO + LFP-2	0,7492	0,7693	0,7848	0,7322
NMC + LFP-2	0,8068	0,7738	0,7892	0,7834

Table 13. Weighted value of the selection criterion (0,7 f_1 + 0,05 f_2 + 0,2 f_3 + 0,05 f_4) for each combination

PE configuration	1	2	3	4
LTO + LFP	0,7327	0,7130	0,8183	0,6965
NMC + LFP	0,7430	0,7187	0,8183	0,7504
LTO + 2nd -life	0,8800	0,8560	0,8808	0,8874
NMC + 2nd- life	0,9697	0,9066	0,7788	0,8921
LTO + LFP-2	0,7290	0,7645	0,7755	0,7126
NMC + LFP-2	0,7730	0,7550	0,7571	0,7633

4.4 The selected HESS configuration

Based on the above results and considerations, several solutions are applicable in terms of battery type and power electronics interface selection. The 2nd-life cells result in poor optimization results due to the relatively high price at the moment and limited data available, even though this may change in the coming years, depending on the market evolution. Due to practical constraints and low availability on the market, LTO cells are discarded. Also, it is preferred to combine both PE interface solutions (configurations 3 or 4), in order to ensure modularity and enable higher-fidelity modelling for further testing and evaluation of the solution.

Finally, the solution combining NMC and LFP-2 battery modules (see Table 1) with PE configuration 4 is selected, with modularity in each of the PE interfaces. The final configuration for the iSTORMY system for this solution is shown in Table 14.

Table 14. Final configuration for the iSTORMY HESS

Combination	Chemistry	Module Configuration	Battery Voltage Nom. (V)	Energy (kWh	PE Interface-2					PE Interface-1		System Lifetime (Years)	System Efficiency (%)	TCO in 10 years (€)
					AC-DC No.	DC-DC No.	Power AC-DC (kVA)	Vdclink (V)	Power DC-DC (kVA)	No. of modules	Power rating (kVA)			
24	NMC	3s7p	153	53,5	-	-	-	-	-	3	25	18,2	96	58.290
	LFP2	6s1p	348	52,2	1	2	33	730	16,5	-	-			

4.5 Levelized cost of storage

In order to evaluate the selected solution with regard to the project objective and KPI of cost reduction, the **Levelized cost of Storage (LCOS)** is discussed in this section. It is calculated using (21), considering the investment cost in terms of CAPEX only for the PE interfaces and battery packs, the OPEX with system losses and replacement costs of the batteries, the residual value of batteries and the total energy request to the system over 10 years in order to reach a value in [€/kWh/cycle].

$$LCOS\left[\frac{€}{kWh\cdot cycle}\right] = \frac{CAPEX+OPEX-residual.cost}{E_{tot\_req}\times 365\times 10} \tag{21}$$

The residual value for the batteries, considered as used battery modules, is calculated in (22) [15].

$$B_{used} = B_{new}\times B_{health}(1-B_{reuse}-B_{discount}) \tag{22}$$

where B_{used} is the buying price of a 2nd-life battery in year N; B_{new} is the price of new batteries of similar capacity in year N in [€/kWh]; B_{health} is the SoH of the battery [%] taken to 80%; B_{reuse} is the re-purposing cost [%] taken to 15% and $B_{discount}$ is the discount factor [%].

With these considerations, the LCOS obtained for the selected solution in 2021 is 0,10 €/kWh/cycle. Attention has to be paid to the fact that the calculations here consider the prices of today, which are very likely to decrease in the coming years, but only consider the costs of batteries and PE interfaces. A more detailed analysis will be performed in WP5 in order to compare the results with the KPIs defined in D1.2.

5 Discussion and Conclusions

This deliverable presented the work performed in Task 3.1 where a fast co-design optimization and sizing framework has been developed for the HESS in iSTORMY, considering different battery packs and PE interfaces. Medium-fidelity models have been considered for 4 battery cell technologies, based on pre-testing and characterization performed in WP2. Low-fidelity electro-thermal models have been considered for the PE interfaces based on efficiency maps from the OEMs, together with a preliminary reliability assessment. The EMS has been considered in parallel with the work in WP4, in order to split the power between the HE and HP battery packs, considering an actual load profile from the use cases defined in D1.1.

Different combinations of battery pack technologies and PE interfaces have been considered in the optimization, based on the system specifications and constraints. The results from the optimization are presented in order to decrease the system cost over 10 years, and increase the system efficiency, the battery packs lifetime and the PE interfaces lifetime. Finally, battery pack chemistries, configurations and sizes are selected together with the PE architecture, topology and sizing.

In particular, LFP cells are selected for the HE battery pack and NMC cells are considered for the HP battery pack, based on the consortium estimations and available information with regard to cost and cyclability. In particular, 2^{nd}-life batteries are not a viable option at the moment due to relatively high cost and limited market maturity, but they may become a very interesting option in the coming years. The combination of both PE interfaces is considered to connect the battery packs to the grid. These will be further modelled with Digital Twin and failure mechanisms within the frame of WP3. A preliminary LCOS has also been evaluated for the system as of year 2021 and further analyses will be performed in WP5, also based on actual measurements.

6 Risk Register

Possible risks identified linked to this activity/report

Risk No.	What is the risk	Probability of risk occurrence[1]	Effect of risk[1]	Solutions to overcome the risk
WP3	No risks identified at this stage (linked to the work reported)	/	/	/

[1)] Probability risk will occur: 1 = high, 2 = medium, 3 = Low

7 References

1. Boonluk, P., Siritaratiwat, A., Fuangfoo, P., & Khunkitti, S. (2020). Optimal siting and sizing of battery energy storage systems for distribution network of distribution system operators. Batteries, 6(4), 1–16. https://doi.org/10.3390/batteries6040056
2. Irena.org. 2021. [online] Available at: <https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2017/Oct/IRENA_Electricity_Storage_Costs_2017.pdf> [Accessed 19 November 2021].
3. Nanophosphate, ”Nanophosphate, Lithium-Ion Prismatic Pouch Cell, AMP20M1HD-A. ”https://www.buya123products.com/uploads/vipcase/468623916e3ecc5b8a5f3d20825eb98d.pdf [Online, accessed 15-Nov-2021]
4. Yang, Yongheng, et al. "Design for reliability of power electronic systems." Power electronics handbook. Butterworth-Heinemann, 2018. 1423-1440.
5. Ruthardt, Johannes, et al. "Junction Temperature Control Strategy for Lifetime Extension of Power Semiconductor Devices." 2020 22nd European Conference on Power Electronics and Applications (EPE'20 ECCE Europe). IEEE, 2020.
6. Park, Heesung. "Numerical assessment of liquid cooling system for power electronics in fuel cell electric vehicles." International Journal of Heat and Mass Transfer 73 (2014): 511-520.
7. Military Handbook MIL HDBK 217F: Reliability Prediction of Electronic Equipment. USA Department of Defense. Washington, USA, 1991. December. Available at http://snebulos.mit.edu/projects/reference/MIL-STD/MIL-HDBK-217F-Notice2.pdf.
8. Chakraborty, Sajib, et al. "Reliability Assessment of a WBG-based Interleaved Bidirectional HV DC/DC Converter for Electric Vehicle Drivetrains." 2020 Fifteenth International Conference on Ecological Vehicles and Renewable Energies (EVER). IEEE, 2020.
9. Sankarkumar, Rayavarapu Srinivasa, and Rajasekar Natarajan. "Energy management techniques and topologies suitable for hybrid energy storage system powered electric vehicles: An overview." International Transactions on Electrical Energy Systems 31.4 (2021): e12819.
10. Omar, Noshin, et al. "SuperLIB Project–Analysis of the Performances of the Hybrid Lithium HE-HP Architecture For Plug-In Hybrid Electric Vehicles." World Electric Vehicle Journal 6.2 (2013): 259-268.
11. Marchi, B., S. Zanoni, and M. Pasetti. "A techno-economic analysis of Li-ion battery energy storage systems in support of PV distributed generation." *Proceedings of the 21st Summer School F. Turco of Industrial Systems Engineering, Naples, Italy* (2016): 13-15.
12. n. null.agent.Cambridge Econometrics:Cambridge Econometrics, "Study on energy prices, costs and their impact on industry and households : final report.", Op.europa.eu, 2021. [Online]. Available: https://op.europa.eu/en/publication-detail/-/publication/16e7f212-0dc5-11eb-bc07-01aa75ed71a1. [Accessed: 15- Nov- 2021]
13. K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, “A fast and elitist multiobjective genetic algorithm: NSGA-II,” IEEE Trans. Evol. Comput., vol. 6, no. 2, pp. 182–197, Apr. 2002.
14. Tran, Dai-Duong, et al. "Modeling and Co-design Optimization for Heavy Duty Trucks." The 31st International Electric Vehicles Symposium and Exhibition. 2018.
15. Chakraborty, Sajib, et al. "Multiobjective GA Optimization for Energy Efficient Electric Vehicle Drivetrains." 2021 Sixteenth International Conference on Ecological Vehicles and Renewable Energies (EVER). IEEE, 2021.
16. Haram, Mohammed Hussein Saleh Mohammed, et al. "Feasibility of utilising second life EV batteries: Applications, lifespan, economics, environmental impact, assessment, and challenges." Alexandria Engineering Journal 60.5 (2021): 4517-4536.

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#	Partner short name	Partner Full Name
1	VUB	VRIJE UNIVERSITEIT BRUSSEL
2	PWD	POWERDALE
3	CEG	CEGASA ENERGIA S.L.U.
4	CEA	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES
5	MGEP	MONDRAGON GOI ESKOLA POLITEKNIKOA JOSE MARIA ARIZMENDIARRIETA S COOP
6	ZIG	ZIGOR RESEARCH & DEVELOPMENT AIE
7	EDF	ELECTRICITE DE FRANCE
8	TNO	NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO
9	PT	PRODRIVE TECHNOLOGIES BV
10	GW	GREENWAY INFRASTRUCTURE SRO
11	AIT	AIT AUSTRIAN INSTITUTE OF TECHNOLOGY GMBH
12	UNR	UNIRESEARCH BV

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