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

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Deliverable Report

D5.5 – Report on Life Cycle Assessment of the use cases

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Publishable summary

The iSTORMY project aims to develop and evaluate an innovative hybrid system designed for the stationary energy storage system (ESS) to the electric grid. By integrating high-energy (HE) lithium iron phosphate (LFP) batteries and high-power (HP) nickel manganese cobalt (NMC) batteries, the hybrid system optimizes energy and power performance while addressing diverse grid applications. This Deliverable D5.5 focuses on assessing the environmental impacts of the iSTORMY system through a Life Cycle Assessment (LCA), comparing its performance against pure HE and pure HP systems in three distinct use cases. This deliverable is closely related to D5.4 of the project, where the Total Cost Ownership of the iSTORMY system is calculated.

The LCA was conducted following the EF 3.1 methodology, in line with European Union recommendations. The selected functional unit, "10 years of service provided by the system," ensures consistent comparison across configurations for each of the use cases. The study's life cycle inventory (LCI) was developed using data provided by project partners, capturing the system's key components: the HE ESS, HP ESS, power electronics optimised for each function, and the assembly and grid integration phase. The analysis identifies the ESS as the dominant contributors to environmental impacts due to the intensive materials and processes involved in battery production.

Three use cases were examined to evaluate the iSTORMY system's performance under varied operational conditions. In Use Case 1, which involves providing frequency support to the pan-European grid, the hybrid system delivered mixed results. While it outperformed the pure HP (NMC) system, it was outperformed by the pure HE (LFP) system. This is attributed to the higher cycling demands placed on the HP component of the hybrid system, compared to the lower cycling requirements of the LFP system. The findings highlight the trade-offs of the hybrid design when addressing applications with intensive power requirements.

For Use Case 2, load levelling at EV charging stations, the iSTORMY system showed the highest environmental impacts among the three configurations. The steep ramping profiles required for EV charging created inefficiencies in the hybrid design, as neither the HE nor HP components operated optimally. The pure HE (LFP) system performed best in this scenario due to its durability and suitability for energy-intensive tasks, while the pure HP (NMC) system aligned better with power-intensive demands. These results emphasize the importance of aligning system design with specific application requirements.

In Use Case 3, which focused on services to island grids with photovoltaic energy shifting and frequency support, the hybrid system outperformed both pure configurations. The HE component handled long-duration PV energy shifting, while the HP component managed rapid power fluctuations, demonstrating the hybrid system’s ability to balance operational demands effectively. This complementary operation minimized cycling intensity and environmental impacts, making the hybrid system the most suitable choice for this use case.

The study concludes that the iSTORMY hybrid system offers significant versatility and potential for complex grid applications, particularly in scenarios requiring both high energy and high power capabilities. However, its environmental performance varies across use cases, highlighting the different needs of the system for each case. By addressing these challenges, the hybrid system can further align with sustainability goals and advance the transition to cleaner energy systems.

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Abbreviations

Symbol / short name	
LCA	Life cycle assessment
EV	Electric vehicle
ESS	Energy storage system
HE	High energy
HP	High power
PCC	Power control cabinet
LFP	Lithium iron phosphate
NMC	Nickel manganese cobalt

1 Introduction

This report outlines the findings of Deliverable D5.5, which centres on the Life Cycle Assessment (LCA) of the iSTORMY technology system, completed under Task 5.4, specifically Subtask 5.4.2. This deliverable evaluates the environmental performance of an innovative energy storage solution, contributing to the EU's broader goals of achieving a climate-neutral economy. This deliverable is closely aligned with D5.4, which presents the Total Cost Ownership of the iSTORMY system from the Subtask 5.4.1.

Stationary energy storage systems (ESS) have a key role in the energy transition towards a climate-neutral economy. By enabling the massive integration of renewable energy-based sources, the use of grid-connected ESS decreases the dependency on fossil fuels and hence reduces the emission of greenhouse gasses, consequently slowing down and lowering the impact on the climate change. The iSTORMY solution optimises the use of different ESS technologies to take advantage of their properties and extend their lifetime.

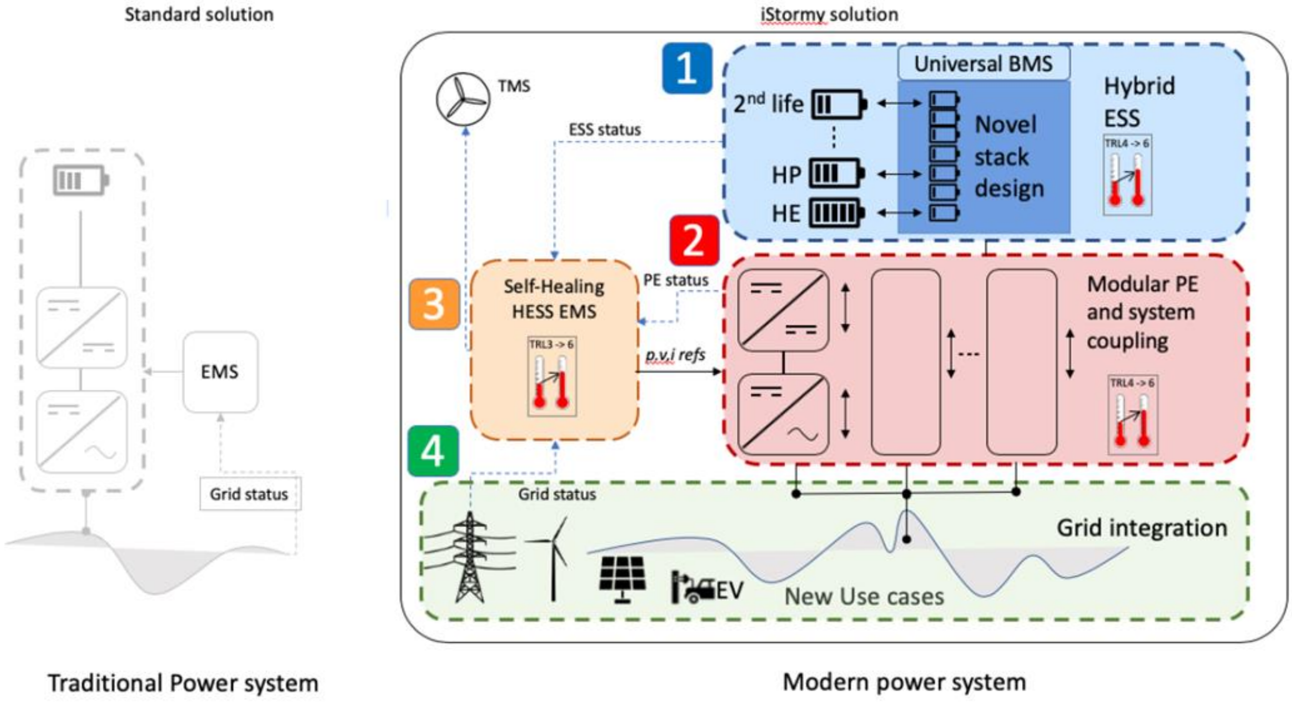

Figure 1: Comparison of the standard and iSTORMY power system

The innovative aspect of the iSTORMY project's hybrid and modular design (Figure 1) lies in its flexible and adaptable architecture that integrates cutting-edge technologies to address key challenges in stationary energy storage systems. The hybridization at the battery pack level allows the combination of different battery chemistries or varying capacities, including first- and second-life batteries, ensuring resource efficiency and sustainability. The modular power electronics interface, utilizing high-efficiency silicon carbide (SiC) devices, enables scalability and seamless integration with diverse battery configurations. Furthermore, the integration of a universal Self-Healing Energy Management Strategy, ensures adaptive control that considers aging and thermal constraints, significantly improving system longevity and reliability. This modular approach not only simplifies cooling system integration but also provides a versatile, future-proof solution that can easily adapt to evolving energy storage needs and technologies.

The 5.4.2 task of the iSTORMY project focuses on evaluating the environmental impacts of the innovative hybrid and modular energy storage system using LCA. This assessment considers all stages of the system's lifecycle, from material extraction and manufacturing to operation, maintenance, and end-of-life, providing a comprehensive understanding of its sustainability performance.

2 Methods and Results

Guided by the Product Environmental Footprint (PEF) methodology (Manfredi et al., 2012) and the ISO 14040/14044 (ISO, 2006a, 2006b), this LCA has characterized multiple environmental indicators associated with the iSTORMY solution. Among these indicators are climate change potential, ozone depletion, aquatic and terrestrial ecotoxicity, photochemical ozone formation, acidification, eutrophication (both terrestrial and aquatic), mineral and water resource depletion, human toxicity (cancer and non-cancer effects), respiratory inorganics, land use transformation, and ionizing radiation. By analysing these indicators, the study has identified key environmental hotspots, thereby providing a foundation for eco-design interventions that can reduce resource demand, enhance efficiency, and improve the environmental performance of the iSTORMY technology throughout its lifecycle.

Primary data for the LCA was gathered from project partners, who provided detailed information on the components and operational characteristics of the iSTORMY system. To complement this primary data, secondary background data was sourced from established LCA databases, such as Ecoinvent (Wernet et al., 2016) and LCA for Experts (Sphera, 2024), as well as from relevant scientific literature. These data sources enabled a robust and accurate assessment of the technology's environmental impacts. This detailed and data-driven approach is in line with iSTORMY's commitment to minimizing the environmental footprint of stationary ESSs, thus supporting the European Union Circular Economy plan (European Commission, 2020) by advancing more sustainable, renewable energy-based solutions. Through this deliverable, the project reinforces the potential for ESS to play a pivotal role in reducing dependency on fossil fuels, supporting renewable integration, and contributing meaningfully to climate change mitigation.

2.1 Goal and scope

The first step of an LCA is the definition of goal and scope, which establishes the foundation for the study. The goal outlines the purpose of the LCA, such as assessing environmental impacts, comparing alternatives, or supporting decision-making. The scope specifies the system boundaries, functional unit (the measurable output for comparison), and assumptions or limitations.

2.1.1 Goal of the iSTORMY LCA study

The goal of the LCA in the iSTORMY project is to evaluate the environmental impacts of its innovative ESS, which combines lithium iron phosphate (LFP) and nickel manganese cobalt (NMC) batteries. This hybrid design optimizes for both high energy (HE) (using LFP batteries) and high power (HP) (using NMC batteries), leveraging the strengths of each chemistry. Moreover, the hybrid system optimises the characteristics of each of the battery types, using the adequate power electronic devices for each of them in an integrated manner (Figure 2). The assessment compares the environmental footprint of the hybrid system to two single-system alternatives: one using only LFP batteries (HE) and the other using only NMC batteries (HP). This comparison is carried out across three specific use cases to identify the environmental benefits and trade-offs associated with the hybrid approach.

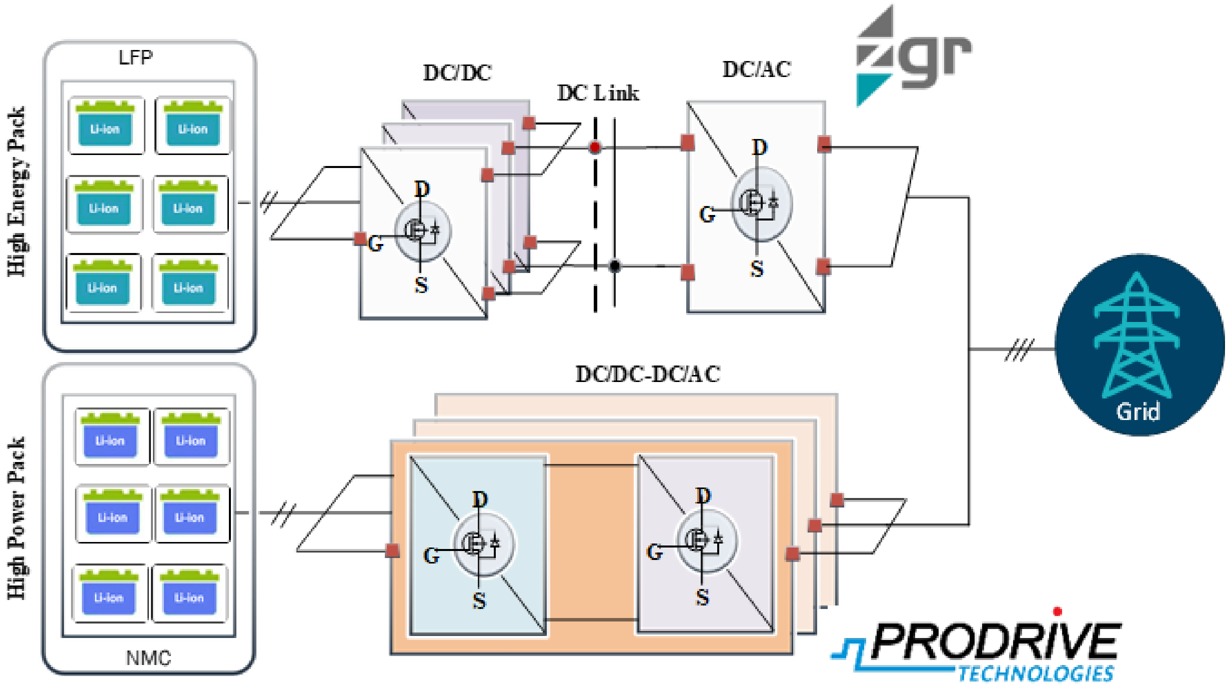

Figure 2: Structure of the iSTORMY system hybrid ESS and power electronics (Source: Prodrive technologies)

The three use cases in the iSTORMY project involve distinct applications of the hybrid energy storage system. These are:

Use Case 1. Stand-alone provision of services to the interconnected pan-European grid – Frequency support: Frequency support is a critical service for ESS due to their fast response times enabled by power electronics. The pan-European grid frequently experiences small frequency deviations due to minor imbalances in power production and consumption. These deviations require a fast-responding asset with high power capacity rather than high energy capacity. The primary goal of this use case is to enhance grid stability during transient events, leveraging the ESS's ability to respond dynamically and optimize its state of charge (SoC) and state of health (SoH).

Use case 2. Pan European grid - Provision of load levelling for electric vehicle (EV) charging service stations: This use case addresses the challenges posed by increasing energy capacity demands from EVs, which require higher-power chargers with steep ramp-up and ramp-down load profiles. To prevent grid instability caused by these load variations, a ramp rate limitation of 10% per minute (based on rated power) will be applied. The hybrid ESS optimises power dispatch between its battery racks to manage the load within these constraints. Additionally, substations supplying high-power EV chargers face maximum power limitations, and the hybrid ESS will help prevent equipment overcurrent and faults by compensating power above contractual limits.

Use case 3. Provision of services to island grids -photovoltaic (PV) shifting and frequency support: In microgrid scenarios with a high share of PV production, frequency stability is a critical issue. Unlike larger grids, microgrids are more vulnerable to frequency deviations due to high production variability from renewable sources such as PV and wind. ESS play a crucial role in mitigating these risks by compensating for short-term imbalances, reducing stress on generators, and minimizing frequency fluctuations.

Table 1 presents an overview of the proposed use cases. These scenarios aim to evaluate the performance of the iSTORMY system compared to the pure HE and HP systems. The LCA study compares the environmental impacts of the system under varied operational conditions.

Table 1: Overview of the use cases

	Use case 1: Stand-alone provision of services to the interconnected pan-European grid – Frequency support	Use case 2: Pan European grid - Provision of load levelling for EV charging service stations.	Use case 3: Provision of services to island grids -PV shifting and frequency support
Network configuration	MV connection point	LV substation connection point	Micro-grid/weak grid environment
Driven by	TSO applicant for technical purpose	DSO & energy supplier for technical and cost optimization	Local grid operators for technical purpose
Operating mode	Continuous delivery	Continuous delivery/interrupted services	Continuous delivery
Dynamic requirement	1s	Few seconds	<1s
Range of Power	1 to 100 MW power range	100 to 600 kVA power range	Results of the micro grid set up
Energy constraint	30 minutes delivery maximum at full power for strong deviation/dead band behaviour	Maximum 10 minutes delivery for RR	Energy oriented for PV shifting

2.1.2 Scope and functional unit

For the LCA study, the scope selected was cradle to grave, considering every life cycle stage: raw materials, manufacturing, transport, use and end of life of every component of the system. Notably, the energy throughput is left out of the impact calculation, considering only the energy consumption by each of the systems when providing the service.

The selected functional unit is "10 years of service provided by the system". The functional unit is aligned with the one chosen for the Total Cost Ownership calculations presented in Deliverable D5.4. This ensures a consistent and fair comparison of the environmental impacts of the three configurations—hybrid, pure HE and pure HP systems—across the three use cases. This functional unit accounts for the operational lifespan of such systems, allowing the study to evaluate their performance and sustainability under equivalent conditions, regardless of differences in system design or application scenarios.

There are key lifetime considerations to account for in regards of each of the three systems. For the power electronic and grid integration components of the system, the lifetime assumption is that they can be used for 15 years and 50 years of operation respectively. However, the ESS batteries are dependent on the configuration and the use case. The lifetime cycle data was derived from project partners and included in D5.4 calculations (Table 2). The batteries were assumed to be unfit for service when they lost 20% of the original capacity due to use (i.e. 80% depth-of-discharge).

Table 2: Relation between use cases, ESS types and lifetime

	Use case 1				Use case 2				Use case 3			
	iSTORMY hybrid		Reference options		iSTORMY hybrid		Reference options		iSTORMY hybrid		Reference options	
	HE part	HP part	pure HE	pure HP	HE part	HP part	pure HE	pure HP	HE part	HP part	Pure HE	Pure HP
Number of charging cycles to reach 80% of original capacity												
Cycle life, T = 25°C (with PCM)	7342	5466	6415	5167	3122	3315	3746	3294	4175	2415	1670	1466
Yearly number of cycles for 3 energy storage solutions												
Yearly number of cycles	715	960	406	834	37	368	97	199	212	204	102	208
For 10 years	7151.3	9595.1	4063.4	8341.0	374.70	3683.7	967.3	1985.6	2121.6	2044.7	1015.3	2084.2
What percentage of the first battery is spent to reach the 10 years lifetime?												
Cycle life. T = 25°C (with PCM)	97%	176%	63%	161%	12%	111%	26%	60%	51%	85%	61%	142%

This indicates that the ESS components of each of the systems are accounted for their lifetime when considering the functional unit of 10 years of service provided. Notably, these estimations were derived based on demanding performance requirements for the iSTORMY system. While this ensures a high-performance response, it also means that the projected lifetimes might be on the shorter side of the possible range.

In term of geographical scope, the assumption was made that the components of the iSTORMY system were manufactured at the main location for each of the partners, sent to Belgium to be assembled (Villers-le-Bouillet, Belgium) and then integrated into the EDF facilities (Écuelles, France)

2.2 Life cycle inventory

The life cycle inventory (LCI) for the iSTORMY system has been developed based on detailed information and data supplied by the project partners, ensuring a comprehensive and accurate foundation for the LCA. Figure 3 presents a simplified structure for the three systems analysed. The inventories presented in this section are simplified to account for the confidentiality of the project partners' technological developments.

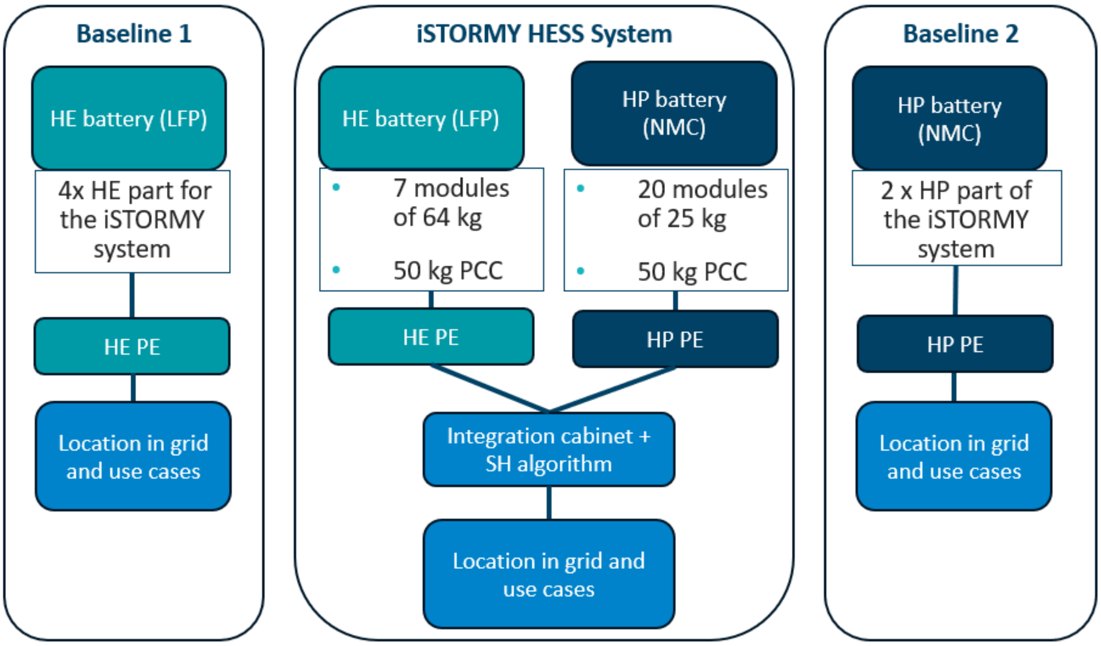

Figure 3: Schematic structure of the iSTORMY and baseline systems

The baseline configurations for the iSTORMY project were selected to enable a comprehensive comparison across all use cases while meeting the overarching goal of designing an interoperable system. The hybrid system was designed with specifications of 100 kWh energy capacity and 100 kW power output to ensure it could serve all three use cases. To ensure fair comparison, both Baseline 1 (HE system) and Baseline 2 (HP system) were defined to meet the same power and energy ratings as the hybrid system. This required oversizing the HE system in power and the HP system in energy, reflecting the inherent trade-offs of single-system configurations.

The main difference between the systems is the ESS part, Table 3 presents the three ESS configurations considered for the LCA study.

Table 3: Characteristics of the battery packs considered

Parameter	iSTORMY Hybrid Battery Pack			Baseline 1	Baseline 2
	HE battery	HP battery	Total hybrid battery	HE battery pack	HP battery pack
Modules	64 kg; 48V; 160 Ah; 8 kWh, easy connection, no cooling	25 kg; 51V; 50Ah; 2,5 kWh, rack format, fan cooling	not applicable	7 pieces of: 64 kg; 48V; 160 Ah; 8 kWh, easy connection, no cooling	2 pieces of: 25 kg; 51V; 50Ah; 2,5 kWh, rack format, fan cooling
N. of modules	7	20	not applicable	28	40
Config	7s1p	4s5p	not applicable	7s1p	4s5p
Voltage (V)	336	204	not applicable	336	204
Capacity (Ah)	160	250	not applicable	640	250
Energy (kWh)	54	51	**105**	215	**105**
Power (kW)	32	92	**124**	**124**	189

Considering the structure of the iSTORMY system as well as the information provided by each of the partners, the LCI table was divided into 5 different components: the HE ESS, the HP ESS, the HE power electronics, the HP power electronics, and the assembly and integration of the system.

2.2.1 High Energy ESS

The simplified inventory table for one module (64.3 kg) of the HE ESS, with the corresponding fraction of the PCC (50kg for 7 modules) provided by CEG is presented in Table 4.

Table 4: Simplified inventory for the high-energy battery (LFP)

Component	Type	Unit	Quantity
Raw Materials			
Cell	LFP cathode, graphite anode	Kg	45
Housing	Low density polyethylene (LLDPE)	Kg	11.41
Cables	Copper, plastic	Kg	2.31
Metal busbars	Aluminium, steel	Kg	1.52
Plastics	Polyethylene, polyester	Kg	1.18
BMS	Copper, plastics, electronics	Kg	2.87
PCC	Electronic components	kg	7.14
Manufacturing			
Synthesis of cell	Electrical energy (China)	kWh	2717
Rest of components and assembly	Electric energy (Spain)	kWh	252
Transport			
Truck	Articulated lorry transport, Euro 5	tkm	705
Ship	Transoceanic ship	tkm	827
Plane	Cargo plane	tkm	43
Use phase			
Energy losses for 10 years operation	Electric energy (France)	kWh	150
End of life			
Transport to waste treatment site	Articulated lorry transport, Euro 5	tkm	12
Battery recovery/ recycling	Pyrometallurgy	kg	44
Rest of components recycling	Standard recycling	kg	18
Battery incineration	Incineration of hazardous waste	kg	9

2.2.2 High Power ESS

The simplified inventory table for one module (25.5 kg) of the HP ESS with the corresponding fraction of the PCC (50kg for 20 modules) and the fraction for the battery boxes (3 boxes for 20 cabinets) provided by CEG is presented in Table 5.

Table 5: Simplified inventory for the high-power battery (NMC)

Component	Type	Unit	Quantity
Raw Materials			
Cell	NMC cathode, graphite anode	Kg	12.67
Housing	Low density polyethylene (LLDPE)	Kg	7
Cables	Copper, plastic	Kg	1.16
Metal busbars	Aluminium, steel	Kg	1.52
Plastics	Polyethylene, polyester	Kg	0.3
BMS	Copper, plastics, electronics	Kg	2.87
PCC	Electronic components	Kg	2.5
Metallic boxes	Steel	kg	19.5
Manufacturing			
Synthesis of cell	Electrical energy (China)	kWh	3336
Rest of components and assembly	Electric energy (Spain)	kWh	100.5
Transport			
Truck	Articulated lorry transport, Euro 5	tkm	281
Ship	Transoceanic ship	tkm	329
Plane	Cargo plane	tkm	17.3
Use phase			
Energy losses for 10 years operation	Electric energy (France)	kWh	52.5
End of life			
Transport to waste treatment site	Articulated lorry transport, Euro 5	tkm	3.8
Battery recovery/ recycling	Pyrometallurgy	kg	12.67
Rest of components recycling	Standard recycling	kg	26
Battery incineration	Incineration of hazardous waste	kg	12.8

2.2.3 High Energy Power electronics

The simplified inventory table for the HE power electronics (237kg) component provided by ZIG is presented in table 6.

Table 6: Simplified inventory for the high-energy power electronics

Component	Type	Unit	Quantity
Raw Materials			
Transformer Core	Steel,	Kg	74.6
Primary Windings	Copper Wire	Kg	42.4
Secondary Windings	Copper Wire	Kg	28.2
Control Module	Plastic, Electronics	Kg	7.1
Cooling System (Fan)	Copper, Aluminum	Kg	25.2
Insulation	Epoxy Resin	Kg	12.4
Housing	Aluminum	Kg	19
Busbars	Copper, Insulation (PVC)	kg	5.1
Monitoring Equipment	Plastic, Metal, Electronics	Kg	2.3
Human-Machine Interface	Glass, Plastic, Metal	Kg	1.6
Mounting and Support Structures	Steel, Aluminum	Kg	13.5
Safety Components	Copper, Steel	Kg	6.6

Component	Type	Unit	Quantity
Manufacturing			
Manufacturing electronics	Electrical energy (China)	kWh	1756
Rest of components and assembly	Electric energy (Spain)	kWh	84
Transport			
Truck	Articulated lorry transport, Euro 5	tkm	73
Ship	Transoceanic ship	tkm	6162
Plane	Cargo plane	tkm	-
Use phase			
Energy losses for 10 years operation	Electric energy (France)	kWh	-
End of life			
Transport to waste treatment site	Articulated lorry transport, Euro 5	tkm	23.7
Components recycling	Standard recycling	kg	215.2
Incineration/Landfill	Incineration of hazardous waste	kg	21.8

2.2.4 High Power optimised power electronics

The simplified inventory table for the HP power electronics (139kg) component provided by PT is presented in table 7.

Table 7: Simplified inventory for the high-power power electronics

Component	Type	Unit	Quantity
Raw Materials			
Boost board	Electronic board	Kg	15.8
Dual Active Bridge board	Electronic board	Kg	23.9
Rectifier Board	Electronic board	Kg	33.4
Control board	Electronic board	Kg	1.4
EMC filter board	Electronic board	Kg	2.7
Backplane total	Copper, aluminum, plastic	Kg	5.6
Cooling system (Fan)	Steel, Aluminum	Kg	4.5
Aluminum housing	Aluminum	Kg	12.8
Switch gear	Silicon, Copper	Kg	3.4
Cabinet steel	Steel	Kg	7.0
Cabinet plywood	Thickness 5.5mm: 3.3kg/m2	Kg	16.0
Cabling mass 16mm2	0.19 kg/m incl. isolation.	Kg	1.4
Cabling mass 35mm2	0.40 kg/m incl. isolation.	Kg	11.2
Manufacturing			
Manufacturing electronics	Electrical energy (China)	kWh	1030
Rest of components and assembly	Electric energy (Netherlads)	kWh	49
Transport			
Truck	Articulated lorry transport, Euro 5	tkm	42.8
Ship	Transoceanic ship	tkm	3614
Plane	Cargo plane	tkm	-
Use phase			
Energy losses for 10 years operation	Electric energy (France)	kWh	-
End of life			
Transport to waste treatment site	Articulated lorry transport, Euro 5	tkm	19.3
Components recycling	Standard recycling	kg	125
Incineration/Landfill	Incineration of hazardous waste	kg	12.9

2.2.5 System integration

The simplified inventory table for the complete system assembly and integration provided by VUB and EDF is presented in table 8.

Table 8: Simplified inventory for the system assembly and integration.

Component	Type	Unit	Quantity
Raw Materials			
Electrical panel	Copper, Electronic board	Kg	5.8
Container	Steel, Rockwool	Kg	2000
Cables	Copper Wire	Kg	13.4
Concrete pad	Cement, quartz, aggregate	Kg	2250
Reinforcement bar	Steel	Kg	60
Equipotential belt	Copper, plastic	Kg	40
Low voltage system breaker	Copper, plastics, steel	Kg	8.2
Manufacturing			
Manufacturing energy	Electrical energy (Europe)	kWh	6430
Transport			
Truck	Articulated lorry transport, Euro 5	tkm	1797
Use phase			
Energy losses for 10 years operation	Electric energy (France)	kWh	-
End of life			
Transport to waste treatment site	Articulated lorry transport, Euro 5	tkm	215
Components recycling	Standard recycling	kg	2127
Incineration/Landfill	Incineration of hazardous waste	kg	2250

2.3 Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) for the iSTORMY system evaluates the environmental impacts of its hybrid and modular energy storage design across three configurations (hybrid, pure HE, and pure HE) and three use cases. These use cases are significantly different from each other. Therefore, the comparison is separated between each of the cases. The life cycle inventory (section 2.2) was built using data from project partners, and the EF 3.1 method (European Commission, 2022) was chosen for the impact assessment, aligning with European Union recommendations. This method allows for a detailed and standardized evaluation of the system's environmental performance.

2.3.1 Results for Use case 1

For Use Case 1, the iSTORMY system demonstrates mixed environmental performance when compared to the two single-system configurations. While it performs better than the pure HP (NMC) system, it falls short when compared to the pure HE (LFP) system as can be seen in Table 9. The savings columns show the environmental reductions of the iSTORMY system compared to the pure HE (LFP) and pure HP (NMC) systems, respectively.

Table 9: Complete EF 3.1 results for Use case 1. NOTE (*): Compared to the hybrid system

EF 3.1 impact categories	iSTORMY	Reference options			
	hybrid	pure HE	Savings(*)	pure HP	Savings(*)
Acidification [Mole of H+ eq.]	4.2E+02	3.2E+02	-29.9%	4.7E+02	11.6%
Climate Change - total [kg CO2 eq.]	3.1E+04	2.2E+04	-39.0%	3.6E+04	12.3%
Climate Change, biogenic [kg CO2 eq.]	6.6E+01	4.9E+01	-35.8%	6.9E+01	3.6%
Climate Change, fossil [kg CO2 eq.]	3.1E+04	2.2E+04	-39.0%	3.5E+04	12.3%
Climate Change, land use and land use change [kg CO2 eq.]	4.7E+01	3.9E+01	-21.6%	5.1E+01	7.8%
Ecotoxicity, freshwater - total [CTUe]	8.5E+05	6.2E+05	-37.5%	9.8E+05	12.9%
Ecotoxicity, freshwater inorganics [CTUe]	5.3E+05	3.8E+05	-39.5%	6.1E+05	12.5%
Ecotoxicity, freshwater organics [CTUe]	3.2E+05	2.4E+05	-34.4%	3.7E+05	13.7%
Eutrophication, freshwater [kg P eq.]	3.8E+01	3.0E+01	-27.9%	4.3E+01	11.6%
Eutrophication, marine [kg N eq.]	4.3E+01	3.0E+01	-41.9%	4.9E+01	12.6%
Eutrophication, terrestrial [Mole of N eq.]	4.9E+02	3.5E+02	-37.6%	5.5E+02	11.6%
Human toxicity, cancer - total [CTUh]	1.4E-03	1.0E-03	-33.1%	1.6E-03	13.8%
Human toxicity, cancer inorganics [CTUh]	4.6E-05	3.6E-05	-27.8%	5.1E-05	9.2%
Human toxicity, cancer organics [CTUh]	1.3E-03	9.9E-04	-33.3%	1.5E-03	13.9%
Human toxicity, non-cancer - total [CTUh]	3.3E-03	2.6E-03	-27.2%	3.7E-03	11.6%
Human toxicity, non-cancer inorganics [CTUh]	3.1E-03	2.4E-03	-26.8%	3.5E-03	11.5%
Human toxicity, non-cancer organics [CTUh]	2.2E-04	1.7E-04	-31.8%	2.5E-04	11.9%
Ionising radiation, human health [kBq U235 eq.]	6.4E+03	6.0E+03	-7.0%	7.1E+03	10.3%
Land Use [Pt]	2.4E+05	1.7E+05	-38.8%	2.6E+05	7.0%
Ozone depletion [kg CFC-11 eq.]	8.5E-04	5.1E-04	-67.0%	1.1E-03	19.7%
Particulate matter [Disease incidences]	2.0E-03	1.4E-03	-44.4%	2.2E-03	11.2%
Photochemical ozone formation, human health [kg NMVOC eq]	1.6E+02	1.1E+02	-41.0%	1.8E+02	12.7%
Resource use, fossils [MJ]	5.6E+05	4.2E+05	-32.5%	6.5E+05	13.6%
Resource use, mineral and metals [kg Sb eq.]	5.2E+00	3.8E+00	-39.0%	6.0E+00	12.2%
Water use [m^3 world equiv.]	2.1E+04	1.6E+04	-28.3%	2.4E+04	14.3%

This outcome is largely influenced by the operational demands placed on the hybrid system. The HP (NMC) portion of the hybrid design undergoes a high level of cycling to meet the fast-response and high-power requirements essential for frequency support. This intensive cycling accelerates wear and increases the associated environmental impacts due to the more resource-intensive nature of NMC batteries. In contrast, the HE (LFP) portion of the hybrid system, which is designed for high-energy capacity, experiences less frequent cycling. Therefore, the iSTORMY hybrid system saves an average of 12% environmental impacts compared to the pure HP alternative.

Meanwhile, the pure HE (LFP) system achieves better environmental performance in this use case, where the iSTORMY system performs around 35% worse environmentally. The total capacity of the pure HE system is much higher than the iSTOMRY system, and thus requires less cycling overall to deliver the same 10-year service provision defined in the functional unit. The inherent durability and resource efficiency of LFP batteries in high-energy applications further contribute to their superior performance in this scenario.

This highlights a key trade-off in the hybrid approach for Use case 1: while the system is optimized for flexibility and versatility, the environmental impacts are influenced by the cycling intensity required for the HP component.

Figure 4 provides a graphical representation of the scales of impacts for the iSTORMY system, compared to the pure HE and pure HP, to better understand the savings or absence of environmental savings for two key categories: the Climate Change - total [kg CO2 eq.] and Resource use, mineral and metals [kg Sb eq.].

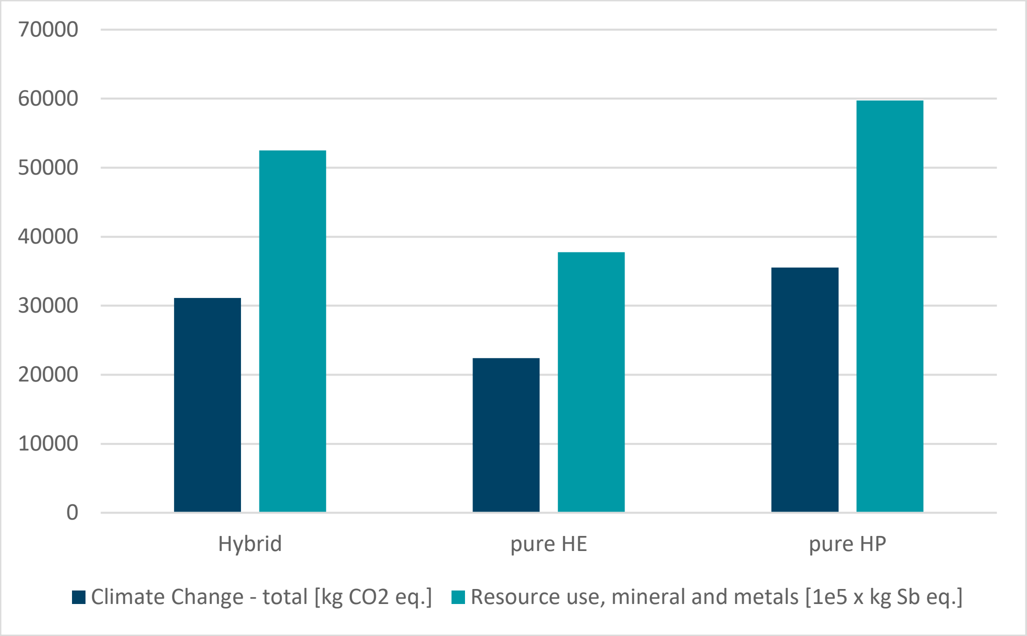

Figure 4: Environmental impacts for Climate Change and Resource use in Use case 1

2.3.2 Results for Use case 2

For Use Case 2, the iSTORMY system demonstrates the highest environmental impacts compared to the pure technology alternatives, as can be seen in Table 10. The savings columns show the environmental reductions of the iSTORMY system compared to the pure HE (LFP) and pure HP (NMC) systems, respectively. This is primarily due to the specific operational requirements of load levelling for EV charging stations, which place unique demands on the hybrid system. In this scenario, both the HE (LFP) and HP (NMC) components of the hybrid design are utilized, but neither operates optimally for this use case.

The pure HE (LFP) system performs significantly better (generating 48% less environmental impacts than the hybrid system) in this use case, due to its durability and ability to handle energy-intensive tasks with fewer cycles. Similarly, the pure HP (NMC) system, while less environmentally efficient than the LFP-based configuration, still outperforms the hybrid design, generating 18% less impacts in average. This is because the HP system's design aligns more closely with the power-intensive demands of this application, avoiding the inefficiencies introduced by combining two distinct battery types in the hybrid system.

Table 10: Complete EF 3.1 results for Use case 2. NOTE (*): Compared to the hybrid system

EF 3.1 impact categories	iSTORMY	Reference options			
	hybrid	pure HE	Savings(*)	pure HP	Savings(*)
Acidification [Mole of H+ eq.]	2.4E+02	1.6E+02	**-47.3%**	2.0E+02	**-19.1%**
Climate Change - total [kg CO2 eq.]	2.0E+04	1.3E+04	**-51.1%**	1.7E+04	**-18.2%**
Climate Change, biogenic [kg CO2 eq.]	4.2E+01	2.8E+01	**-53.4%**	3.2E+01	**-34.5%**
Climate Change, fossil [kg CO2 eq.]	2.0E+04	1.3E+04	**-51.2%**	1.7E+04	**-18.2%**
Climate Change, land use and land use change [kg CO2 eq.]	2.7E+01	2.0E+01	**-37.0%**	2.3E+01	**-21.5%**
Ecotoxicity, freshwater - total [CTUe]	5.8E+05	4.1E+05	**-43.0%**	5.2E+05	**-13.2%**
Ecotoxicity, freshwater inorganics [CTUe]	3.3E+05	2.1E+05	**-56.5%**	2.7E+05	**-20.0%**
Ecotoxicity, freshwater organics [CTUe]	2.6E+05	2.0E+05	**-28.7%**	2.4E+05	**-5.6%**
Eutrophication, freshwater [kg P eq.]	2.2E+01	1.5E+01	**-45.1%**	1.8E+01	**-18.2%**
Eutrophication, marine [kg N eq.]	2.7E+01	1.7E+01	**-57.5%**	2.3E+01	**-20.0%**
Eutrophication, terrestrial [Mole of N eq.]	3.1E+02	2.0E+02	**-51.6%**	2.6E+02	**-19.7%**
Human toxicity, cancer - total [CTUh]	1.1E-03	8.7E-04	**-27.5%**	1.1E-03	**-5.0%**
Human toxicity, cancer inorganics [CTUh]	2.7E-05	1.8E-05	**-45.6%**	2.2E-05	**-22.7%**
Human toxicity, cancer organics [CTUh]	1.1E-03	8.5E-04	**-27.1%**	1.0E-03	**-4.7%**
Human toxicity, non-cancer - total [CTUh]	1.9E-03	1.3E-03	**-45.7%**	1.6E-03	**-18.9%**
Human toxicity, non-cancer inorganics [CTUh]	1.7E-03	1.2E-03	**-45.2%**	1.5E-03	**-18.8%**
Human toxicity, non-cancer organics [CTUh]	1.3E-04	8.3E-05	**-52.7%**	1.1E-04	**-20.2%**
Ionising radiation, human health [kBq U235 eq.]	3.2E+03	2.7E+03	**-18.1%**	2.9E+03	**-10.2%**
Land Use [Pt]	1.5E+05	1.0E+05	**-55.5%**	1.2E+05	**-29.2%**
Ozone depletion [kg CFC-11 eq.]	5.2E-04	2.7E-04	**-92.0%**	4.5E-04	**-16.2%**
Particulate matter [Disease incidences]	1.3E-03	8.5E-04	**-54.3%**	1.1E-03	**-20.7%**
Photochemical ozone formation, human health [kg NMVOC eq]	9.8E+01	6.3E+01	**-56.7%**	8.2E+01	**-19.7%**
Resource use, fossils [MJ]	3.4E+05	2.3E+05	**-46.9%**	2.9E+05	**-15.0%**
Resource use, mineral and metals [kg Sb eq.]	3.1E+00	1.9E+00	**-61.5%**	2.5E+00	**-22.8%**
Water use [m^3 world equiv.]	1.2E+04	8.2E+03	**-44.3%**	1.0E+04	**-13.2%**

Figure 5 provides a graphical representation of the impacts for the iSTORMY system, compared to the pure HE and pure HP, to show the higher impacts of the hybrid system for the Use case 2 in two representative environmental impact categories: the Climate Change - total [kg CO2 eq.] and Resource use, mineral and metals [kg Sb eq.].

The iSTORMY solution's poor performance in this use case underscores a limitation of the hybrid approach when faced with tasks requiring frequent and rapid power adjustments. It highlights the need for careful selection of system configurations based on the specific operational context to achieve optimal environmental outcomes. Additionally, it suggests opportunities for improving hybrid systems by refining energy management strategies or reconfiguring battery roles to better match the requirements of load levelling applications.

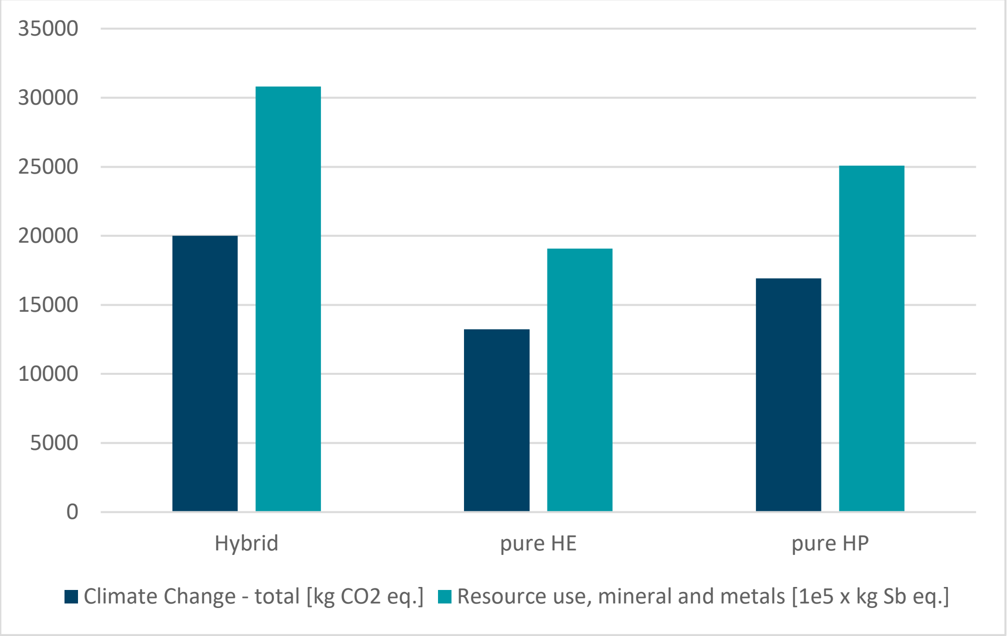

Figure 5: Environmental impacts for Climate Change and Resource use in Use case 2

2.3.3 Results for Use case 3

For Use Case 3, the iSTORMY system outperforms both the pure HE (LFP) and pure HP (NMC) reference systems in terms of environmental impacts (Table 11). The savings columns show the environmental reductions of the iSTORMY system compared to the pure HE (LFP) and pure HP (NMC) systems, respectively. This use case, which involves providing services to island grids with photovoltaic energy shifting and frequency support, highlights the advantages of the hybrid approach. The hybrid system's ability to leverage the strengths of both battery types proves especially effective in managing the high variability of renewable energy production while ensuring frequency stability in the microgrid.

The HE (LFP) system struggles in this scenario due to its lower suitability for handling frequent and rapid power adjustments required by the high variability of PV generation. Although LFP batteries are robust and have a lower environmental footprint per cycle, their slower response times and limitations in power-intensive tasks result in suboptimal performance for this application. In this regard, the hybrid system represents an average of 12% environmental impact savings compared to the pure HE reference.

Similarly, the HP (NMC) system, while more suited for rapid power delivery, has higher environmental impacts due to its resource-intensive production and shorter overall lifespan, making it less ideal for the combined requirements of energy shifting and frequency support. Using the hybrid system compared to the pure HP saves up to 38% of the environmental impacts for the 10-year period.

The main cause for these savings is that the iSTORMY system’s hybrid design enables it to balance the operational demands efficiently. The HP (NMC) component manages the rapid power fluctuations, while the HE (LFP) component provides the necessary energy capacity for shifting PV generation over longer periods. This complementary operation reduces cycling intensity on each battery type, optimizing performance and minimizing environmental impacts. This use case demonstrates the clear advantage of the hybrid approach in scenarios requiring both HE and HP capabilities, underscoring the versatility and environmental benefits of the iSTORMY system in managing complex grid challenges.

Table 11: Complete EF 3.1 results for Use case 3. NOTE (*): Compared to the hybrid system

EF 3.1 impact categories	iSTORMY	Reference options			
	hybrid	pure HE	Savings(*)	pure HP	Savings(*)
Acidification [Mole of H+ eq.]	2.5E+02	3.1E+02	20.1%	4.2E+02	41.1%
Climate Change - total [kg CO2 eq.]	2.0E+04	2.2E+04	8.4%	3.2E+04	37.6%
Climate Change, biogenic [kg CO2 eq.]	4.3E+01	4.7E+01	9.3%	6.2E+01	30.3%
Climate Change, fossil [kg CO2 eq.]	2.0E+04	2.2E+04	8.4%	3.2E+04	37.6%
Climate Change, land use and land use change [kg CO2 eq.]	2.9E+01	3.8E+01	24.3%	4.6E+01	37.9%
Ecotoxicity, freshwater - total [CTUe]	5.8E+05	6.0E+05	4.2%	8.9E+05	34.9%
Ecotoxicity, freshwater inorganics [CTUe]	3.3E+05	3.7E+05	11.3%	5.4E+05	39.7%
Ecotoxicity, freshwater organics [CTUe]	2.5E+05	2.3E+05	-7.1%	3.4E+05	27.3%
Eutrophication, freshwater [kg P eq.]	2.2E+01	2.9E+01	21.9%	3.8E+01	41.5%
Eutrophication, marine [kg N eq.]	2.7E+01	3.0E+01	8.5%	4.4E+01	39.0%
Eutrophication, terrestrial [Mole of N eq.]	3.1E+02	3.4E+02	10.4%	4.9E+02	37.7%
Human toxicity, cancer - total [CTUh]	1.1E-03	1.0E-03	-6.1%	1.5E-03	27.3%
Human toxicity, cancer inorganics [CTUh]	2.8E-05	3.5E-05	20.6%	4.5E-05	38.9%
Human toxicity, cancer organics [CTUh]	1.1E-03	9.8E-04	-7.1%	1.4E-03	27.0%
Human toxicity, non-cancer - total [CTUh]	1.9E-03	2.5E-03	23.5%	3.3E-03	42.2%
Human toxicity, non-cancer inorganics [CTUh]	1.8E-03	2.3E-03	23.7%	3.1E-03	42.3%
Human toxicity, non-cancer organics [CTUh]	1.3E-04	1.6E-04	20.3%	2.2E-04	42.1%
Ionising radiation, human health [kBq U235 eq.]	3.5E+03	5.8E+03	39.9%	6.3E+03	45.2%
Land Use [Pt]	1.6E+05	1.7E+05	8.1%	2.3E+05	33.3%
Ozone depletion [kg CFC-11 eq.]	5.0E-04	4.9E-04	-1.8%	9.4E-04	46.8%
Particulate matter [Disease incidences]	1.3E-03	1.3E-03	1.5%	2.0E-03	34.7%
Photochemical ozone formation, human health [kg NMVOC eq]	9.8E+01	1.1E+02	9.5%	1.6E+02	39.4%
Resource use, fossils [MJ]	3.4E+05	4.1E+05	16.9%	5.8E+05	41.4%
Resource use, mineral and metals [kg Sb eq.]	3.1E+00	3.7E+00	14.8%	5.3E+00	41.5%
Water use [m^3 world equiv.]	1.2E+04	1.6E+04	22.7%	2.2E+04	44.0%

To visually complement the data provided in Table 11, Figure 6 shows the environmental impacts of all three systems (hybrid, pure HE and pure HP) in use case 3 for two environmental impact categories: the Climate Change - total [kg CO2 eq.] and Resource use, mineral and metals [kg Sb eq.].

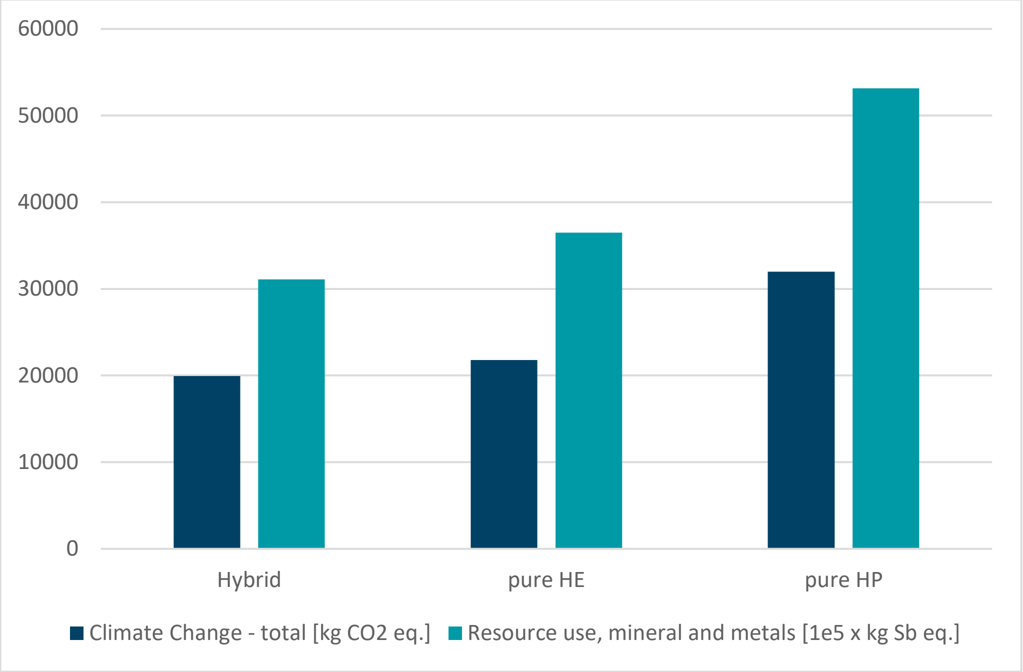

Figure 6: Environmental impacts for Climate Change and Resource use in Use case 3

2.4 Interpretation

The LCIA results of the iSTORMY system provide critical insights into the environmental performance of a hybrid energy storage solution. Also, these results are compared to pure HE (LFP) and pure HP (NMC) alternatives across three distinct use cases. A more detailed look analysis the results provides key insights for the improvement of the future hybrid systems. The iSTORMY system consists of several interconnected components. These components include the HE ESS (LFP), the HP ESS (NMC), the power electronics for the HE system, the power electronics for the HP system, and the assembly and integration phase for grid connectivity. Together, these elements enable the hybrid system to meet its diverse operational requirements across the three use cases.

Among these components, Figure 7, Figure 8 and Figure 9 show that the environmental impacts are naturally dominated by the ESS in all three use cases. The production, use, and end-of-life management of the ESS, especially the HP part account for the majority of the system’s environmental burden. This ranges from 40% of the Climate Change burden in Use case 3 to over 60% of the impacts related to Resource use for Use case 2. The main cause for this is the high number of cycles required from the HP part of the ESS in all three Use cases. Due to the high % of impact related to the ESS, the choice of the batteries is key in the environmental performance of the iSTORMY system.

The LCIA results therefore provide critical insights into the design of the storage systems. Detailed analyses are also performed in this chapter, however they are highly dependent on the system sizing and actual cell technology. The findings underscore the importance of focusing on optimizing the ESS components in future developments. Enhancing battery durability, reducing material intensity, and improving recycling and reuse strategies for both HE and HP systems can significantly mitigate the environmental impacts of hybrid energy storage solutions like iSTORMY. Additionally, refining energy management strategies to reduce cycling intensity can further prolong battery lifespan is a clear pathway for better environmental performance. Incorporating the benefits of its self-healing algorithms and active diagnostics that were part of the project, but not fully reflected in the LCA. For a more comprehensive assessment of the system, these features could reduce cycling intensity, extend battery lifespan, and optimize resource utilization.

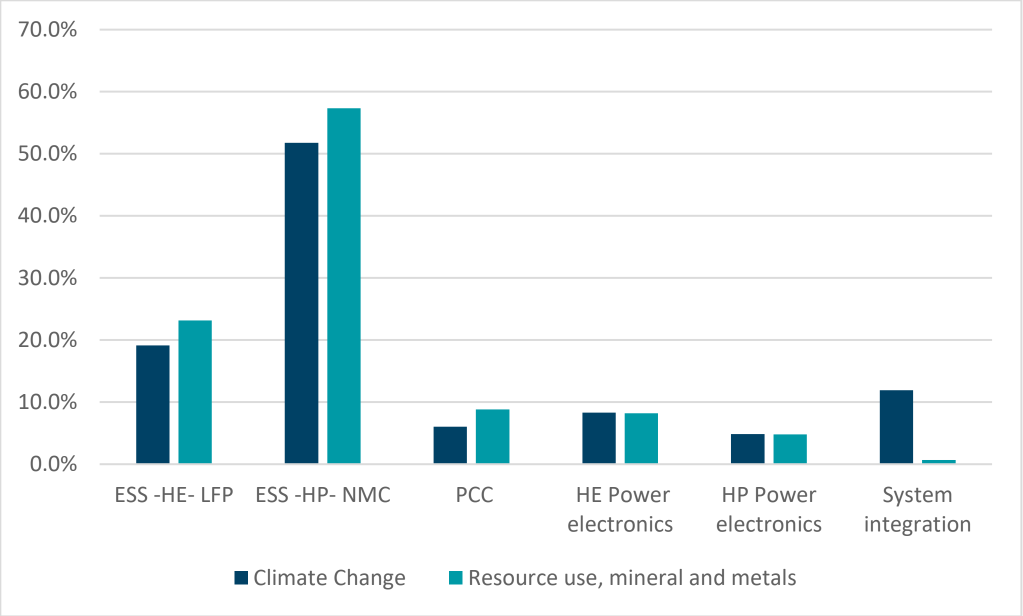

Figure 7: Percentage of impact by each component of iSTORMY system for Use case 1

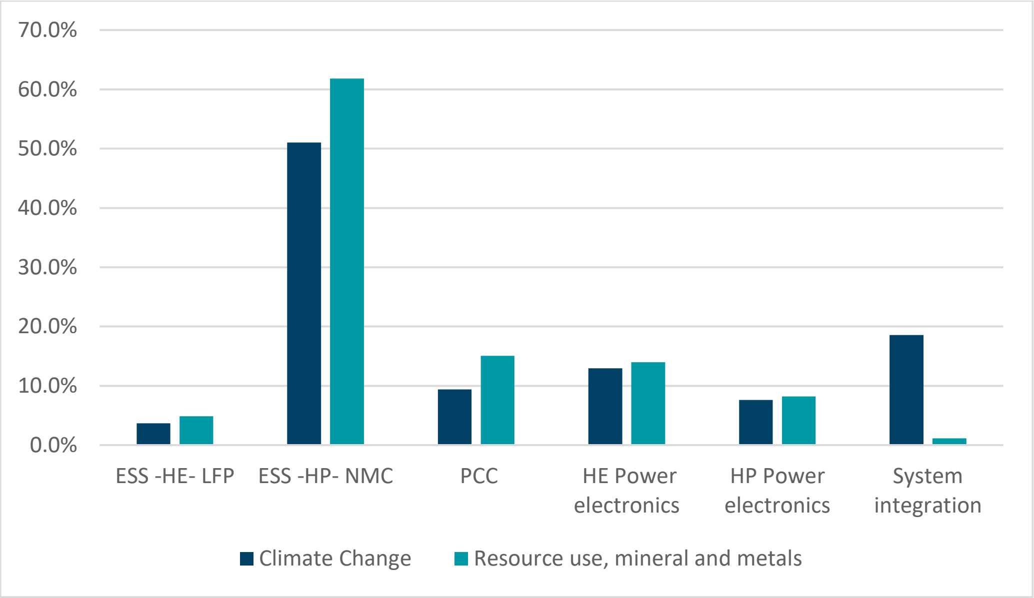

Figure 8: Percentage of impact by each component of iSTORMY system for Use case 2

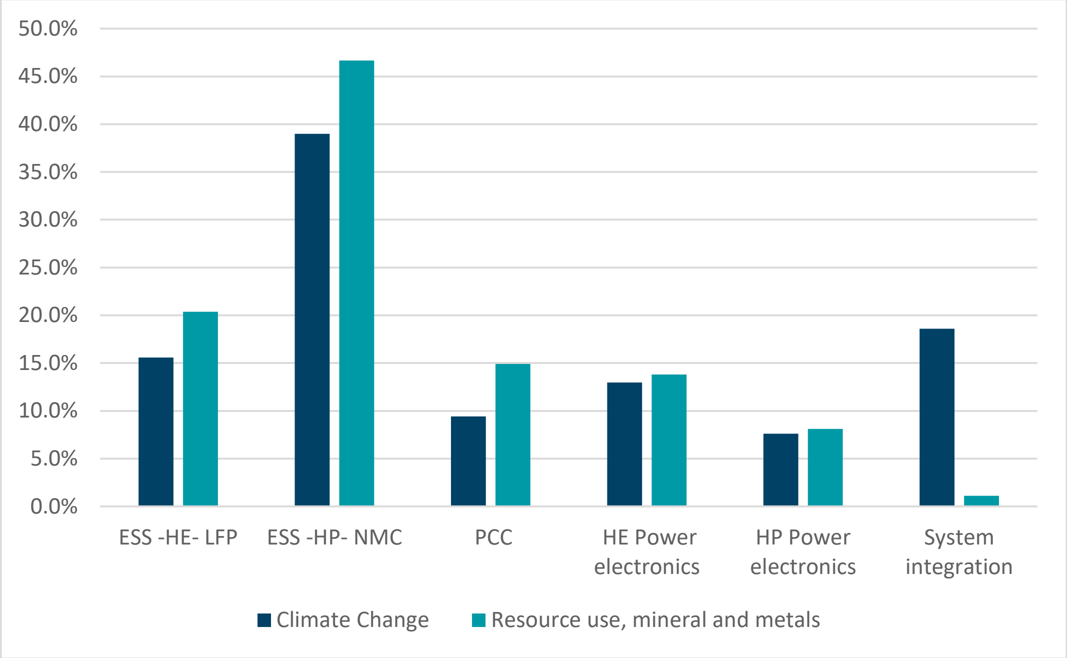

Figure 9: Percentage of impact by each component of iSTORMY system for Use case 3

3 Conclusions

This deliverable D5.5 of the iSTORMY project includes an in-depth analysis of its environmental performance across three distinct use cases, by means of an LCA. This evaluation focuses on the hybrid energy storage solution of the project, comparing it to pure HE (LFP) and pure HP (NMC) reference configurations.

The iSTORMY hybrid system’s performance across three use cases, highlights its strengths and limitations compared to single-system configurations. In Use Case 1 (frequency support for the pan-European grid), the hybrid system performs better than the pure HP (NMC) system due to the HE (LFP) component's durability but is outperformed by the pure HE system, which requires less intensive cycling. In Use Case 2 (load leveling in EV charging stations), the hybrid system faces challenges in handling steep ramping profiles, resulting in higher environmental impacts. The pure HE system excels in energy-intensive tasks, while the pure HP system is better suited for power-intensive demands, showing the importance of aligning designs with specific operational needs. However, in Use Case 3 (services to island grids with PV energy shifting and frequency support), the hybrid system clearly outperforms both alternatives. Its combination of HE and HP components effectively manages renewable energy variability and frequency stability, minimizing environmental impacts and optimizing performance.

These results highlight the hybrid system's flexibility and adaptability, though direct comparisons between configurations are limited by differences in design and ratings. The hybrid system's broader advantages, including reduced material use, extended lifespan, and operational efficiency, emphasize its value in meeting diverse application requirement. The choice of pure HE and HP as baselines highlights the advantages of the hybrid system. By combining HE and HP batteries, the hybrid configuration can better balance energy and power ratings without excessive oversizing, optimizing both design and operation. This hybridization not only reduces material use and energy consumption but also enables operational efficiencies and innovations that extend the system's lifetime, benefits not achievable with single-system designs.

For all three use cases, the evaluation of lifetime and environmental impacts of the iSTORMY system is greatly influenced by the estimation of cycles undergone during the 10 years of service. The cycling model used for the iSTORMY system was based on a highly demanding operational profile, ensuring robustness across all three use cases. However, this operational profile may not fully represent real-world conditions, where the system is unlikely to consistently face such extreme demands. In practical applications, milder operational conditions would significantly reduce cycling intensity, extending the lifespan of the system's components. Moreover, the incorporation of self-healing algorithms and active diagnostics can further mitigate the ageing of the battery packs, proactively addressing degradation and enhancing system performance. The hybrid system also offers greater flexibility compared to pure HE or HP technologies, allowing it to adapt more effectively to varying operational requirements. These combined advantages (reduced wear, extended lifespan, and operational flexibility) would substantially lower the environmental impacts associated with battery wear and replacement. This makes the iSTORMY hybrid system a more sustainable, versatile, and environmentally favourable solution for diverse energy storage applications.

Likewise, while the LCA provides valuable insights into the environmental impacts of the system, the differences in ratings and design requirements between the hybrid system and the single-system baselines generate challenges in direct comparison scenarios. The hybrid system shows advantages such as offering flexibility and adaptability across diverse use cases and reduced material needs through minimized oversizing. Its ability to balance HE and HP requirements underscores its potential as a versatile and environmentally favourable solution. These findings reinforce the importance of a tailored approach to hybrid system design and energy management to maximize both environmental and operational performance across diverse use cases. The insights gained will guide future developments to further optimize the sustainability of hybrid ESS.

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#	Partner short name	Partner Full Name
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3	CEG	CEGASA ENERGIA S.L.U.
4	CEA	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES
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