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An Extended Approach to the Evaluation of Energy Storage Systems: A Case Study of Li-Ion Batteries

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Abstract: Energy storage technologies can act as flexibility sources for supporting the energy transition, enabling the decarbonisation of the grid service provision and the active engagement of the customers (both prosumers and consumers), opening for them new business opportunities. Within storage technologies, Lithium-ion (Li-ion) batteries represent an interesting solution for dealing with the majority of these services. In this context, this study addresses an evaluation of economic, environmental and geopolitical risks with reference to the critical raw materials used in the manufacturing of Lithium Iron Phosphate (LFP) Li-ion batteries. The assessment entailes grid and prosumer services that these batteries can provide. The exploited economic indicator is the Levelised Cost of Storage, whereas six environmental indicators are used for environmental impact estimation. Cycle stages accounted for in the analysis are the manufacturing and use phases. Finally, the evaluation of the impact of critical raw materials is performed by deploying a Supply Risk indicator, which is instead assessed considering every single material and the overall risk for the battery. High-risk materials are represented by Graphite and Phosphorous. Results denote that, for each service, the number of cycles and the discharge duration are pivotal to make the investment economically and environmentally sustainable. The reduction in the Net Import Reliance, as well as the increase in the Recycling Rate, could sensibly reduce the risk associated with battery raw materials.

Keywords: energy storage; li-ion; sustainability; life cycle costing; environmental LCA; critical raw materials

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1. Introduction

The rapid pace of the increasing anthropogenic greenhouse gas (GHG) emissions pushed governments worldwide to sign the Paris agreement in 2015. The aim of this treaty was to keep the global average temperature increase 2 °C below the pre-industrial level [1]. To reach this target, the European Union (EU) introduced a set of policy initiatives, known as the European Green Deal. Apart from the long-term goal, consisting in reaching net-zero GHG emissions, the EU also established mid-term goals by 2030: a reduction in GHG emissions of at least 40%, an increase in the share of renewable energy in the total energy consumption to at least 32% and an improvement of at least 32.5% in energy efficiency [2]. A new proposal of the European Commission (EC) includes a higher threshold of reduction in GHG emissions, reaching 55% of GHG emissions by 2030. The role of energy in achieving EU climate and energy targets is pivotal, since it is responsible for around 75% of EU GHG emissions [3]. The main strategy for reducing emissions in the energy sector is represented by the shift from fossil fuel generation to a renewable-based one. Particularly, variable renewable energy sources (VRES), represented by solar and wind generators, have negligible emissions during the operational phase and, since that, their capacity is massively growing in the EU [4]. In particular, the average share of electricity from VRES generation, including both wind and solar generation, in the EU electricity mix increased from around 0.16% in 2004 to 20.54% in 2019 [5]. However, VRES also represent an issue for the electricity system, due to their aleatory and intermittency [6]. These issues can be managed from the system through the exploitation of flexibility sources, such as energy storage and conversion technologies, demand response and VRES curtailment [7]. Within energy storage technologies, Lithium-ion (Li-ion) batteries are characterised by high round-trip efficiency, high energy density and low self-discharge; since that, they emerged as one of the most technically efficient energy storage solutions, both for stationary as well as for mobility applications [8,9]. Their crucial role in the clean energy transition is testified by the launching of the European Battery Alliance (EBA) by the EC in 2017 [10]. The aim of the EBA is to ensure a sustainable battery value chain, considering both the access to raw materials as well as the environmental and economic sustainability of these batteries throughout their whole life cycle. The theme of critical raw materials of batteries was also highlighted from several reports made by the EC [11–13]. An EC platform was released in 2015 for recognising the main stocks and flows in the batteries' value chains [13]. In [11], the EC underlined the dependency of foreign countries on battery raw materials, especially in the first stages of the supply chain. Although it is expected that the EU, through the construction of gigafactories, will reach 69% of its demand of Li-ion batteries in 2025, an upstream raw materials segment still remains an open issue [12]. On the basis of the previous considerations, the supply risk of non-fossil fuel raw materials is gaining much more interest compared to the past. This topic can be outlined in different ways, according to the geographical and temporal boundaries, as well as to the followed approach and the target of the study [14]. In many cases, the risk assessments focus on the economy as the object of the evaluation [15–21]. In others, the study object is instead a specific product [22–27]. Geographical boundaries involved the United Kingdom [15], United States [20,21] and the EU [16–19] economies. Geographical boundaries of product-oriented analyses are, in some cases, on a global scale [22,23]. In most of the cases, product-oriented analyses are made at country or regional level [24–26,28]. When specified, the time-frame of these analyses covers either the short or the medium term, since the long-term analyses are usually more focused on resource depletion [29]. Some works emphasise the word *criticality*, which accounts for probability and vulnerability aspects of raw materials [16–19,26]. Therefore, the criticality concept overlaps with the classic risk definition, as pointed out in [24,30]. Vulnerability aspects, representing the potential damages linked to the supply disruption, are usually tackled considering proxy indicators, such as the Gross Value Added of these materials in industrial sectors [16–19]. Other authors instead take into account the mass of the material with respect to a reference value [24,27]. The methodological framework of these works is aligned with the Life Cycle Sustainability approach, since the presence of Characterisation Factors is linked to raw material deployment at the product level. Another important issue usually tackled in sustainability studies (and not investigated in this paper) is the environmental life cycle analysis of the batteries [31–34]. In [31], a techno-economic and environmental comparison was carried out between combined cycle gas turbines (CCGTs) and battery energy storage systems (BESSs). The results showed that switching from the electricity produced from CCGTs to the electricity discharged from BESSs, fed by high shares of renewable energy, could reduce greenhouse gas emissions by 86%. Other works instead investigated the role of BESSs in frequency-based grid services [32,33]. In detail, a comparative life cycle assessment between coal-based power plants (CPPs) and BESSs was made, showing that BESSs have better environmental performances compared to CPPs, especially when they are used to switch from fossil-fuel-based power plants to renewable-based ones. According to the previous considerations, the aim of this work is two-fold, and it consists of the following:

- Providing an extended methodology applied to Li-ion batteries that includes environmental, economic and supply risk features; the latter ones are investigated for the manufacturing and the use phase of the batteries.
- Exploiting the methodology to assess the variability of these features according to the service provided by Li-ion batteries.

The last domain (i.e., supply risk) was accounted for to enlarge the perspective on sustainability and investigate the possible trade-offs among conflicting domains. The rest of this paper is structured as follows:

- Section 2 presents the metrics deployed for the proposed assessment, as well as the case study.
- Section 3 shows the quantitative estimation of the analysis, sub-divided for each deployed metric; furthermore, a sensitivity analysis and a discussion of the overall results are carried out.
- Section 4 presents the main achievements of this work, the concluding remarks and the possible future applications.

2. Materials and Methods

The sustainability assessment of the Storage accounts for the environmental Life Cycle Assessment (eLCA), the Life Cycle Costing (LCC) as well as for the geopolitical risk of materials (GRMs). Within the boundary of the investigated system are included both the manufacturing and the operational phase. The end-of-life is instead outside the system boundaries due to the lack of information related to it. The methodological approach is aligned to LCA methodology, defined by ISO 14040 and ISO 14044 [35]. Figure 1 shows the overall methodological approach. The first step is the Goal and Scope Definition. This consists of clearly defining the Aim of the study, the Functional Unit as well as the Boundaries of the System. The second step is the Inventory Analysis, in which useful data are collected and scaled according to the Functional Unit for the assessment. Then, as the third step, the Impact Assessment aims at quantifying the impact of selected Impact Categories. Finally, the Interpretation is exploited for the critical evaluation of the Impact results from the analyst. Further potential adjustments can be made from the LCA analyst in the previous steps, according to the results obtained (e.g., the expansion of the system boundaries).

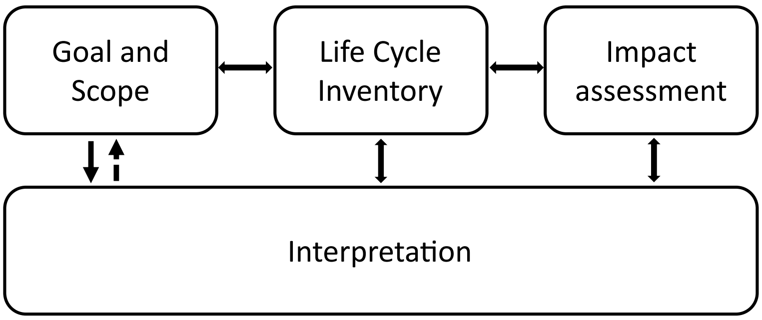

Figure 1. Schematic representation of Life Cycle assessment stages according to ISO 14040-14044.

2.1. Characterization of the Energy Storage Use: Overview of the Electrical Services

Regarding the services that Energy Storage Systems can provide, they can be split into grid-based, customers-based (i.e., Energy Arbitrage services) and seasonal services. Grid services include all the services required to maintain a proper operation of the power system. Selected services were reported in Table 1. Within grid-based services, a further distinction can be made in Frequency Containment Reserve (FCR), automatic Frequency Replacement Reserve (aFRR), manual Frequency Replacement Reserve (mFRR), Replacement Reserve (RR), Black Start and Congestion Relief and Investment Deferral (CR & ID) [36,37]. In detail, the FCR exploits flexibility sources to limit within certain limits the frequency deviations from the nominal value (50 Hz in Europe). The aFRR acts instead as a further reserve to restore the frequency nominal value and make available again the FCR, while the mFRR is exploited for restoring the FCR and aFRR. In some countries, the RR is deployed as a further restoration tool. Black start represents a further tool in case of electricity system collapse, to energise crucial components (e.g., power plants). CR & ID is a service that enables the proper management of the power congestions and aims to delay grid economic investment (e.g., increasing the power lines' capacity). Energy Arbitrage is instead a service exploited by prosumers (defined in [38] as the network users that consume and produce electrical energy) for obtaining economic profit by the deployment of renewable generation coupled with Storage Systems [39,40]. Finally, seasonal services are exploited for storing energy for long periods of time (i.e., weeks or months). As can be seen in Table 1, each service is characterised according to three main features, namely the response time, the discharge duration and the yearly cycles. These key features represent the minimum requirements that flexibility tools, such as energy storage systems, must have in order to provide the specific service. In detail, the response time is the maximum time for the energy storage to reach its full power, while the discharge duration is the minimum amount of time in which the flexibility source has to deliver energy for satisfying the service considered [41]. Yearly cycles are instead the expected number of cycles made by the storage system for providing that service. However, due to the great uncertainty concerning these features, in most cases they are provided in a range rather than with specific values.

Table 1. Main features of Electricity Services.

Service	Response Time	Discharge Duration	Yearly Cycles	Type
FCR	2–3 s	0.25 h	250–12,000	Grid
aFRR	1–5 s	0.25 h	250–10,000	Grid
mFRR	>5 min	0.25 h	20–50	Grid
RR	>15 min	0.25–1 h	20–50	Grid
Black Start	10 min	1 h	10–20	Grid
CR & ID	min	2–8 h	360–380	Grid
Arbitrage	min	1–10 h	270–300	Customer
Seasonal	min	5–336 h	1–5	-

2.2. Domains of the Analysis

2.2.1. Economic Domain: Life Cycle Costing (LCC)

The evaluation of the LCC (i.e., the costs incurred by the system throughout its entire life cycle) is performed by exploiting the Levelised Cost of Storage (LCOS), defined as the specific cost for discharging a unit of energy. It can be expressed in mathematical terms as follows:

$$\sum_{t=1}^{T} \frac{E_t \cdot LCOS}{(1+i)^t} = TLCC \Rightarrow LCOS = \frac{TLCC}{\sum_{t=1}^{T} \frac{E_t}{(1+i)^t}} \tag{1}$$

In (1), E_t and $TLCC$ represent the energy discharge at year t from the storage and the total Life Cycle Cost, respectively. $TLCC$ is expressed in EUR, and it accounts for Capital Costs, O&M Costs, as well as for Charging Costs and End-of-Life Costs (i.e., including Decommissioning, Disposal and potential Recycling Costs):

$$TLCC = \sum_{t=0}^{T} (C_{cap,t} + C_{O\&M,t} + C_{charge,t}) \cdot (1+i)^{-t} + C_{EOL} \cdot (1+i)^{-(T+1)} \tag{2}$$

$C_{cap,t}$, $C_{O\&M,t}$, $C_{charge,t}$ and C_{EOL} appearing in (2) represent the capital costs, the O&M costs (i.e., the costs associated with operating and maintaining the system, not including replacement costs and charging costs), the Charging Costs and End-of-Life Costs, respectively. E_t can instead be expressed in the following way:

$$E_t = E_{n,t} \cdot DOD_{max} \cdot \eta_{rt} \cdot \kappa_{cy} \tag{3}$$

where $E_{n,t}$, DOD_{max}, η_{rt} and κ_{cy} represent the Energy Capacity of the Energy Storage, the maximum Depth of Discharge, the round-trip efficiency and the number of cycles per year, respectively. Terms appearing in (2) and (3) are properly discounted by the Discounting Factor $(1+i)^t$, where the term i represents the interest rate. The mathematical formulation for the EOL costs is instead slightly different, since they are discounted considering just the year after the end of the useful life of the system $T+1$.

2.2.2. Environmental Domain: Environmental Life Cycle Assessment (eLCA)

The eLCA involves the evaluation of environmental impacts of the investigated products throughout the whole life cycle or part of it. The exploited approach is the Attributional eLCA, which estimates the environmental burdens belonging to the products [42]. Environmental burdens for each Impact Category are computed as follows:

$$EI_z = \sum_{j=1}^{J} e_j \cdot CF_{z,j} \tag{4}$$

where EI_z represents the environmental impacts for the zth environmental domain, e_j is the jth elementary flow and $CF_{z,j}$ is the characterisation factor the zth domain and the jth elementary flow [43]. In detail, elementary flows represent the raw materials and emissions linked to the product under evaluation, and they are normalised according to the functional unit. The functional unit of this work is equal to the lifetime electricity discharged from the storage system. Since the focus of the study is related to the manufacturing and the use phase, the elementary flows can be scaled in the following way:

$$e_j = e_j^{(man)} + e_j^{(use)} \tag{5}$$

As shown in (5), the contribution of the jth elementary flow has been partitioned in the manufacturing phase ($e_j^{(man)}$) and use phase ($e_j^{(use)}$). Flows linked to the manufacturing phase can be further expressed in the following way:

$$e_j^{(man)} = \frac{E_j^{(man)}}{\sum_{t=1}^{T} E_t} \tag{6}$$

where $E_j^{(man)}$ is the jth absolute elementary flow. The generic elementary flow linked to the use phase $e_j^{(use)}$ accounts for the delivering of 1 kWh of electricity, considering the round-trip losses:

$$e_j^{(use)} = \frac{e_j^{(el)}}{\eta_{rt}} \tag{7}$$

where $e_j^{(el)}$ is the jth elementary flow linked to the charge of electrical energy within the storage system. The selected impact categories are listed in Table 2. All the Indicators are quantified through the equivalent units of a reference substance (e.g., for Climate Change is the Carbon Dioxide).

Table 2. Overview of Impact Assessment Categories deployed in this study.

Impact Category	Indicator	Unit of Measure	Brief Description
Climate Change	GWP100	$kg_{CO_{2,eq}}$	Global Warming Potential of Atmospheric emissions of Greenhouse Gases in a 100-year time horizon
Acidification	ACD	$molc_{H+_{eq}}$	Release of H+ ions caused by air emissions of SO_x, NO_x and NH_3
Terrestrial eutrophication	TE	$molc_{N_{eq}}$	Atmospheric nitrogen compounds deposition (NO_x, NH_3)
Freshwater eutrophication	FE	$molc_{P_{eq}}$	Soil and water phosphorous compounds deposition
Marine eutrophication	ME	$kg_{N_{eq}}$	Emissions of nitrogen compounds in marine ecosystems
Resource depletion	RD	$kg_{Sb_{eq}}$	Exploitation of natural resources for the life cycle of the product, compared to the "Reserve Base" of these resources

2.2.3. Geopolitical Domain: Geopolitical Risk of Materials (GRMs)

Concerning the GRMs, the materials included in the analysis are the following ones:

- Lithium Iron Phospate Oxide ($LiFePO_4$);

- Natural Graphite;
- Copper;
- Aluminium.

Particularly, Lithium, Iron and Phosphorus are considered the embedded elements under investigation for $LiFePO_4$. The choice of these battery materials is due to the mass share of these components. In fact, they represent around 45% of the mass of the Battery Pack. Life Cycle stages included within the risk analysis are the extraction and the processing. The choice is related to the fact that bottlenecks (i.e., high concentrations of materials) are usually concentrated on the first stages of manufacturing. The evaluation entails in particular the element embedded within the battery materials and in the upstream supply chain stages. In fact, material flows are computed relying on the mass conservation law and neglecting further conversion losses [44]. The characterisation factors, exploited for the evaluation of the supply risk of the battery materials, are taken from the criticality assessment of the EC for EU-27 [18]. This approach takes into account the supply risk and the economic importance as the two main parameters for the evaluation of the criticality of the materials for the EU-27 economy. Since economic importance is referred to in all the economic sectors, and this analysis is referred to as a specific product, this parameter has been not included in the evaluation [14]. The supply risk SR_m for the mth material is instead exploited as the proxy indicator for the estimation of the risk of the materials and it can be expressed as follows:

$$SR_m = f(HHI, WGI, SI, EoL_{RIR}, NIR) \tag{8}$$

In (8), HHI represents the concentration index of the supplier countries, WGI is the arithmetic average of the six worldwide governance indicators developed by the World Bank [45] (intended to indicate the geopolitical stability of the supplier countries), SI is the substitution index of the material (measuring the physical availability of possible substitute materials, with respect to the assessed ones), EoL_{RIR} is the recycling rate at the end-of-life (i.e., the share of dismantled materials that can be reused instead of virgin materials in a manufacturing process) and NIR is the ratio of the net import and the apparent consumption. In particular, the NIR can be expressed in the following way:

$$NIR = \frac{w_{Imp} - w_{Exp}}{w_{Prod} + w_{Imp} - w_{Exp}} \tag{9}$$

In (9), the terms w_{Imp}, w_{Exp} and w_{Prod} represent the material quantities imported, exported and internally produced (i.e., the domestic production), respectively. It can be seen how the denominator terms can be grouped in an aggregated indicator, called apparent consumption.

A further step to be carried out is the aggregation in $SR_b^{(ec)}$ (i.e., the supply risk normalised with respect to the battery energy capacity) of the supply risk indicator values (i.e., SR_m) taken from the literature, which is achieved by considering the mass share of the materials included in the battery:

$$SR_b^{(ec)} = \sum_{m=1}^{M} SR_m \cdot \omega_m \tag{10}$$

where ω_m is the specific weight of the material, expressed in kg per kWh of energy capacity. Therefore, the supply risk of single materials are deployed as characterisation factors (CFs). The latter ones represent the relative contribution of each materials to the geopolitical risk impact category. The normalised risk SR_b, scaled according to the functional unit (i.e., the lifetime electricity delivered by the Li-ion batteries), is instead equal to:

$$SR_b = SR_b^{(ec)} \cdot \frac{E_{n,t}}{\sum_{t=1}^{T} E_t} \tag{11}$$

In (11), SR_b is expressed in kg per kWh of energy delivered by the storage system throughout its useful life.

2.3. Case Study

2.3.1. Features of the Batteries under Investigation

The systems under study refer to three different Lithium-ion battery plants. The core of the three systems is the Battery Pack is graphically reported in Figure 2. The battery is composed of the module (i.e., the set of battery cells that are connected in series and parallel), the Battery Management System (BMS) and the Cooling System [46]. The module is composed of battery cells, each of them having a cathode, anode, an electrolyte and a separator. Finally, the cathode and anode are characterised by the active part of the electrode and the collectors (apart for small quantities of binders and carbon black to improve conductivity). The latter ones are usually represented by Copper and Aluminium for Li-ion batteries. Since the focus is on the LFP type, a cathode is composed of the Lithium Iron Phosphate as the active material, whereas the anode is made of Graphite.

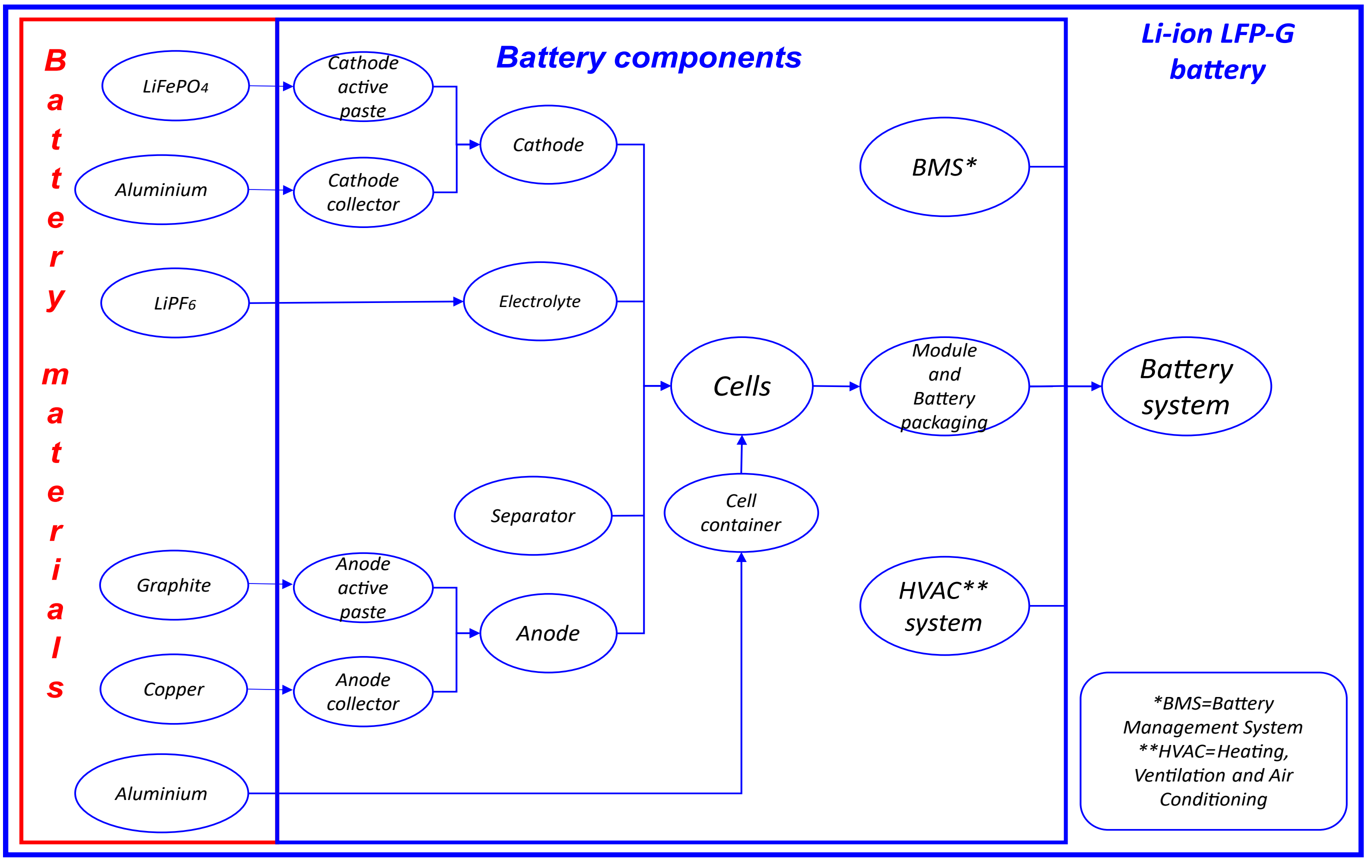

Figure 2. Schematic representation of a LFP battery pack.

Battery plants are specifically declined according to the electricity service provided. Particularly, for the grid services requiring high power, Utility-scale Li-ion batteries can be deployed. For the Arbitrage, it is is instead possible to identify commercial/industrial prosumers and residential ones. The main difference between the the batteries deployed in these applications is the size, with Residential Li-ion Batteries in the order of a few kW_{DC}. The different nominal powers of the three Li-ion battery systems investigated in this work are listed in Table 3. Moreover, the cell voltage is equal to 3.3 V [47]. From the analysis of the state-of-the-art, no detailed data have been found about the battery cell layout, due to the fact that these technologies are generally patented.

Table 3. Main features of different typology of Lithium-ion-based battery plants.

Typology	Size (kW)
Utility-scale	60×10^3
Commercial/industrial	300
Residential	6

The main technical features of the LFP batteries collected from the literature are reported in Table 4 [34,46,48]. The maximum depth of discharge DOD_{max} represents the maximum discharge that the battery can sustain without meeting premature ageing [49,50]. The cycle life expectancy at <70%, named κ_c, is instead the foreseen number of cycle of the battery before it reaches 70% of its original capacity, considering working conditions that do not exceed DOD_{max} [51]. According to the literature data, cycle life expectancy for LFP batteries is variable in the range of 2500–10,000 [34,46–48,52,53]. Main uncertainties depend on the manufacturer, the operating temperatures, the charge/discharge duration and the depth of discharge [53]. An average value of 5000 cycles is selected, according to [47]. However, in case of really fast discharging (e.g., for frequency regulation services) the cycle life of these battery cells can sensibly decrease [53]. In order to tackle this issue, a sensitivity analysis is carried out, and presented in Section 3.4. The assumed battery charge and discharge efficiencies, denoted as $\eta_{DC}^{(ch)}$ and $\eta_{DC}^{(dch)}$, respectively, account for energy losses throughout the electro-chemical conversion. Furthermore, inverter efficiency η_{inv} accounts for conversion losses from DC to AC and vice versa. Finally, round-trip efficiency η_{rt} is obtained through the following formula:

$$\eta_{rt} = \eta_{inv} \cdot \eta_{DC}^{(ch)} \cdot \eta_{DC}^{(dch)} \cdot \eta_{inv} \tag{12}$$

Formula (12) neglects the self-discharge losses in the battery.

Table 4. Main features of LFP battery.

Parameter	Symbol	Value
Max depth of discharge (%)	DOD_{max}	80%
Cycle life expectancy at <70%	κ_c	5000
Battery charge efficiency (%)	$\eta_{DC}^{(ch)}$	98%
Battery discharge efficiency (%)	$\eta_{DC}^{(dch)}$	98%
Inverter efficiency (%)	η_{inv}	95%
Round-trip efficiency (%)	η_{RT}	87%

2.3.2. Scenarios

The assessment of the impacts on the three considered domains (i.e., economic, environmental and geo-political risks with reference to critical raw materials) of LFP battery plants has been carried out by considering five different scenarios characterised by different values of (i) yearly cycles and (ii) discharge duration, according to the different services provided by the batteries. These values are reported in Table 5. In particular, while Scenario A and Scenario E take into account the extreme values of yearly cycles and discharge duration (as found in the specialised literature, such as [36,54,55]), Scenarios B to D aim to consider the variability of these parameters through a sensitivity analysis.

Table 5. Main features of LFP battery plant exploitation, for each service and scenario.

Service	Parameter	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
FCR	Yearly cycles	250	3188	6125	9063	12,000
	Discharge duration (h)			0.25		
aFRR	Yearly cycles	250	2688	5125	7563	10,000
	Discharge duration (h)			0.25		
mFRR	Yearly cycles	20	28	35	43	50
	Discharge duration (h)			0.25		
RR	Yearly cycles	20	28	35	43	50
	Discharge duration (h)	0.25	0.44	0.63	0.81	1
Black start	Yearly cycles	10	13	15	18	20
	Discharge duration (h)			1		
CR & ID	Yearly cycles	360	365	370	375	380
	Discharge duration (h)	2	3.50	5	6.50	8
Arbitrage-Residential	Yearly cycles	270	278	285	293	300
	Discharge duration (h)	1	3.25	5.50	7.75	10
Arbitrage-Commercial	Yearly cycles	270	278	285	293	300
	Discharge duration (h)	1	3.25	5.50	7.75	10

2.3.3. Economic Data

Economic input data for the evaluation of the LCC are shown in Table 6. As can be noted, the cost items are differentiated according to the plant typology (i.e., utility, commercial/industrial and residential). These data have been collected from multiple sources and adjusted to take into account the inflation, the conversion rate between USD and EUR and the different labour rates between the United States and European Union [56,57].

Table 6. Input data for LCC evaluation.

Typology	Battery (EUR/kWh)	Balance of System (EUR/kW)	Installation Costs (EUR/kWh)	Fixed O&M (EUR/kW-yr)	Variable O&M (EUR/MWh)
Utility	180	239	98	10	0.5
Commercial	191	322	439	10	0.5
Residential	237	747	751	10	0.5

The capital cost items reported are the battery cost, the balance of system (BOS) and the installing costs, whereas replacement costs are supposed to be equal to the share of the capital cost of the battery itself. In detail, battery costs include the capital cost incurred for purchasing the battery (i.e., battery modules, rackets and the battery management system). BOS costs instead entail the structural and electrical components, such as the inverters, cables and the energy management system (EMS). Finally, installing costs are the costs incurred for the construction of the battery plant. O&M costs account instead for fixed operational expenses (Fixed O&M) and variable ones (Variable O&M). Further details are presented in Table 7.

Table 7. Cost items deployed in the economic evaluation.

Item	Symbol	Brief Description	Sub-Items
Battery	c_e	Purchase of the batteries	Modules, racks, BMS
Balance of system	c_p	Purchase of the BOS	Inverters, cables, EMS, switchgear, monitor controls, wiring, conduit, foundation, battery containers and inverter house
Installing costs	c_{inst}	Installation of the battery plant	Installation labour and equipment, other soft costs
Replacement costs	c_{rep}	Replacement of the batteries, after they reached their cycle life	Same as battery sub-items
Fixed O&M	c_f	Fixed operating expenses	Planned Maintenance, labor
Variable O&M	c_v	Variable operating expenses	Other non-fuel operating expenses

As shown in Table 6, capital costs decrease with the size, whereas the fixed and variable O&M are assumed to be equal for all the three plant typologies. Another LCC input is the useful life of the battery plants, which was assumed equal to 10 years [57]. As discount rate i, the Weighted Average Capital Cost (WACC) is deployed. WACC for commercially proven and mature technologies is equal to 4% [58]. However, a conservative value of 5% was assumed, aligned with other studies [59]. End-of-Life costs are neglected since the lack of data. Regarding the assessment of the environmental impacts, data in the literature are exploited as the input specifically for the battery pack manufacturing phase [47]. The input electricity for the storage has been hypothesised equal to the EU-27 average mix. Finally, geopolitical risk input data have been collected from several sources, including geological survey institutes [46,47,60–63]. Additionally, materials quantities are collected from [46,47].

3. Results and Discussion

This section shows the numerical results of the work, by considering the environmental, economic and supply risk domains (presented in Section 2.2), as graphically reported in Figure 3. The environmental domain is further broken down into several impact categories, whereas the economic and supply risk contain only one specific impact category.

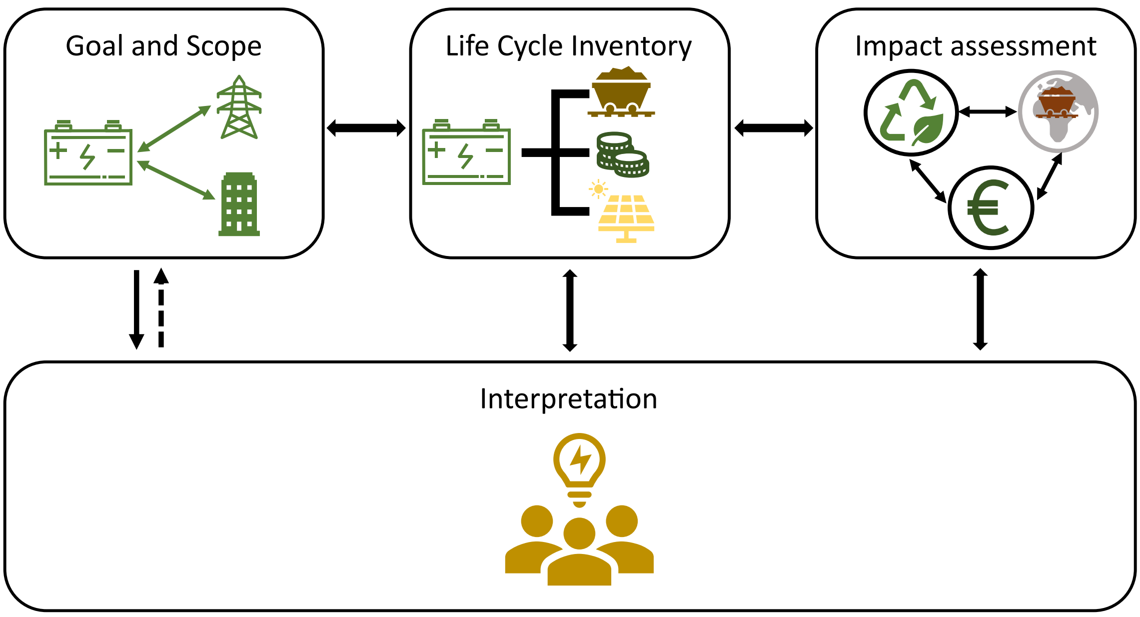

Figure 3. Flow chart of the multi-domain assessment.

3.1. Economic Domain: LCC Results

The results for the LCC parameter are reported in Table 8. The economic evaluation for each service is measured deploying the LCOS indicator and, therefore, the results are expressed in €/MWh. As described in Section 2.3.2, the assessment takes into account five scenarios of exploitation for each service, namely Scenario A, Scenario B, Scenario C, Scenario D and Scenario E. Frequency-related services with high numbers of yearly cycles are characterised by a lower LCOS, compared to the other services. In detail, the FCR and aFRR have ranges of LCOS equal to 98.1–1206.8 €/MWh and 106.9–1206.8 €/MWh. Grid services with lower numbers of cycles are instead characterised by a LCOS higher than 2.3×10^3 €/MWh. In detail, LCOS ranges of mFRR, RR and Black Start are, respectively, equal to $5.8{\times}10^3$–$1.4{\times}10^4$ €/MWh, $2.3{\times}10^3$–$1.4{\times}10^4$ €/MWh and $5.6{\times}10^3$–$1.1{\times}10^4$ €/MWh. These high values are due to the low number of Yearly Cycles (10–50) and the low discharge duration 0.25–1 h, lowering the energy discharged during the operational phase. Finally, CR & ID, Arbitrage-Commercial and Arbitrage-Residential have a LCOS in the range of 210.3–1307.8 €/MWh. Additionally in this case, the higher number of Yearly Cycles determines the lower LCOS, as shown by comparing CR & ID and Arbitrage. A further difference between Arbitrage at commercial/industrial scales and the residential one is due to higher Capital Installing and Replacement Costs for the residential case (see Table 6).

Table 8. LCOS (in EUR/MWh) for every service and scenario.

Service	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
FCR	1206.8	177.9	140.3	112.4	98.1
aFRR	1206.8	200.9	157.1	123.9	106.9
mFRR	14,461.9	10,532.5	8287.2	6834.3	5817.3
RR	14,461.9	6851.0	4237.5	2986.2	2273.8
Black start	11,152.1	8932.5	7452.8	6395.9	5603.2
CR & ID	280.5	242.7	226.5	216.9	210.3
Arbitrage-Commercial	766.1	560.9	514.6	489.4	471.3
Arbitrage-Residential	1307.8	889.8	799.9	753.0	720.6

Moreover, it was investigated that the share of the main economic voices comprised the LCOS indicator, including the initial investment cost (accounted as overnight cost), the replacement cost, the operation and maintenance cost and the charging cost. These results are graphically reported in Figure 4. A frequency-based service characterised by a high number of cycles (i.e., FCR and aFRR), are the only ones for which it is needed to replace the LFP battery stacks throughout the useful life. Indeed, in Scenario B of these two services, the replacement is carried out every two years, whereas for Scenario C, D and E the replacement occurs every year. Despite the high frequency of replacement, the LCOS sensibly decreases with the increase in the number of cycles. In fact, the reduction in LCOS, going from Scenario A to Scenario E, is equal to 92% for FCR and 91% for aFRR. The reasons to have a higher number of cycles and to more frequently replace the battery stack is the reduced value of future discounted cash flows and the fact that only the stack is replaced, whereas the BOS is not affected by the replacement itself. For grid services characterised by a lower number of cycles (i.e., mFRR,RR and Black Start) the charging cost impact on the overall LCOS is almost negligible, with the share varying in the range of 0.4–2.4%. For such services, major contributors are the initial investment costs (79.2–86.6%) and the O&M costs (12.7–19.9%). Since there are no replacements, their contribution is null. Moreover, CR and ID, Energy Arbitrage Commercial and Residential also have a predominant contribution of the initial investment cost (72–91.5%), while the share of the O&M cost does not exceed 7.3% (specifically going from 0.7% to 7.3%). Due to the relatively higher number of cycles for these services compared to mFRR, RR and Black Start (270–380 vs. 10–50), charging cost are instead higher. Particularly, the share of charging cost goes from 4.1% to 25.5%.

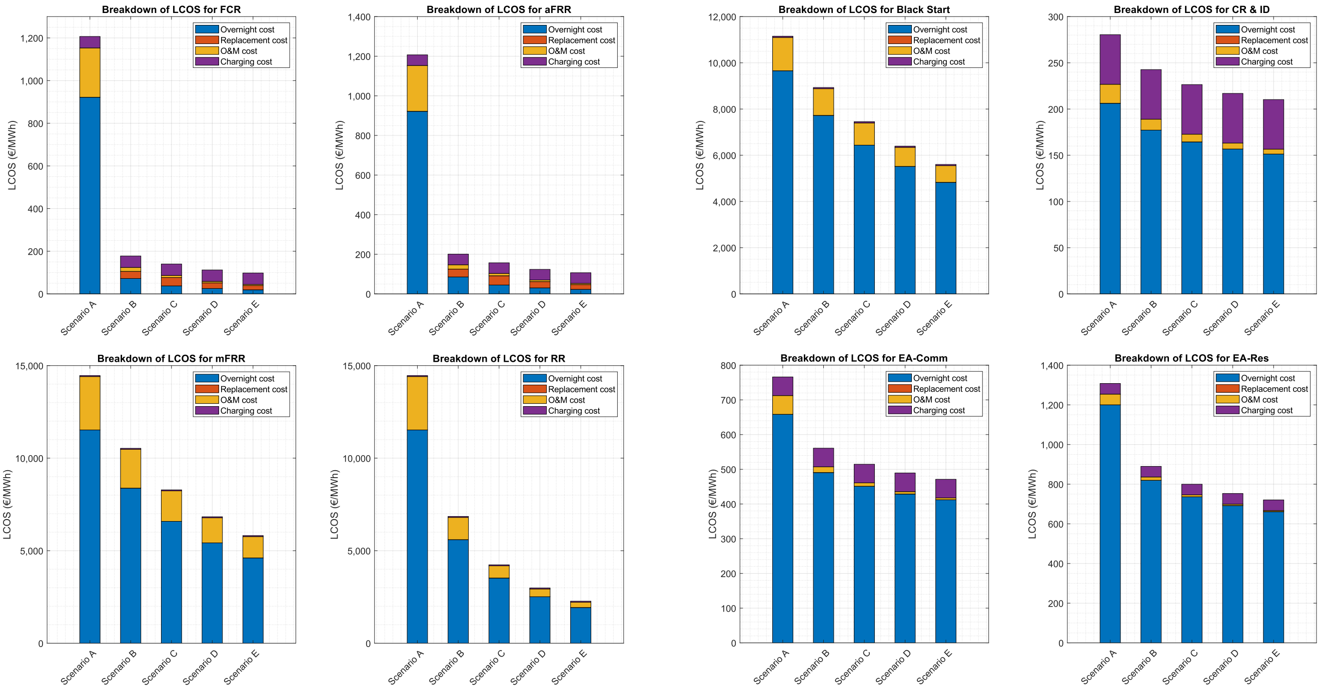

Figure 4. Breakdown of LCOS, for each service and scenario.

3.2. Environmental Domain: eLCA Results

The overall environmental impacts, including both the manufacturing and use phase, are graphically reported in Figure 5. The results are expressed per kWh of electricity delivered from the LFP battery. The GWP varies between 0.47 $kg_{CO_{2,eq}}$/kWh and 0.52 $kg_{CO_{2,eq}}$/kWh for FCR and aFRR. Results are analogous for aFRR, with the only difference represented by the lower boundary (0.473 $kg_{CO_{2,eq}}$/kWh, due to a lower number of yearly cycles (1×10^4 compared to 1.2×10^4). mFRR, RR and Black Start are instead characterised by higher values of GWP, due to the low number of yearly cycles, equal to 20–50 cycles/year for mFRR and RR, and 10–20 for Black Start. The overall GWP for mFRR, RR and Black Start varies, respectively, in the ranges of 0.79–1.28 $kg_{CO_{2,eq}}$/kWh, 0.79–1.28 $kg_{CO_{2,eq}}$/kWh and 1.28–2.10 $kg_{CO_{2,eq}}$/kWh. The same scores for mFRR and RR are related to the fact that the ratio between the energy capacity and the energy discharged is proportional to the number of cycles, and not to the discharge duration. CR and ID, Commercial and Residential Arbitrage are instead characterised by low variability due to a small variation in cycles per year. Values for GWP are around 0.5 $kg_{CO_{2,eq}}$/kWh for CR & ID, and 0.51 $kg_{CO_{2,eq}}$/kWh for the Arbitrage case. In addition, the other environmental impact categories show similar trends, with services with high numbers of cycle and discharge durations characterised by lower impacts. In detail, Acidification values lies in the range of 2.4×10^{-3}–2.8×10^{-3} $molc_{H+_{eq}}$/kWh for FCR and aFRR, 5.1×10^{-3}–1.6×10^{-2} $molc_{H+_{eq}}$/kWh for mFRR, RR and Black Start. Finally, for CR & ID, as well as for Energy Arbitrage, the lower and upper boundaries are between $2.6 \times 10^{-3}$and 2.8×10^{-3} $molc_{H+_{eq}}$/kWh. The Lower and upper boundaries for terrestrial eutrophication, freshwater eutrophication and marine eutrophication lie, respectively, in the ranges of 3.5×10^{-3}–2.1×10^{-2} $molc_{N_{eq}}$/kWh, 0.5×10^{-3}–2.6×10^{-3} $kg_{P_{eq}}$/kWh and 0.4×10^{-3}–3.1×10^{-3} $kg_{N_{eq}}$/kWh. Finally, Resource Depletion impacts vary between $1.3 \times 10^{-5}$and 1.2×10^{-3} $kg_{Sb_{eq}}$/kWh.

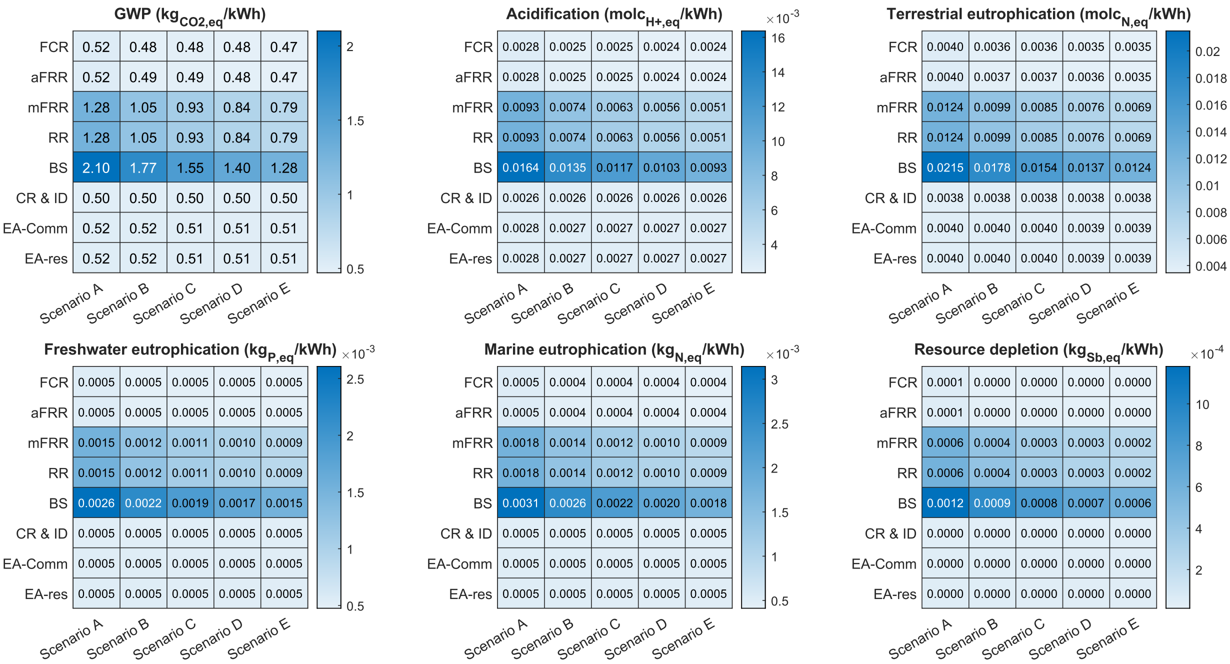

Figure 5. Environmental impacts of Li-ion battery pack for each service and scenario.

Figure 6 reports instead the share of manufacturing and use in environmental impact scores for a selected scenario (Scenario C). Error bars denote the variability with respect to the other scenarios. The share of the use phase for the GWP impact category compared to the overall score is quite high, varying within the range from 87% to 97% for the FCR. The upper threshold of the share of use for the GWP is slightly less for the aFRR, with a value of 96%. The manufacturing phase for the mFRR, RR and Black Start services has a major impact on the overall GWP, with shares of 42–64%, 42–64% and 64–78%, respectively. This effect is also related to the low cycles provided by the batteries for satisfying these services. The impact of the manufacturing phase in the overall GWP for CR and ID, Commercial and Residential Arbitrage is modest, varying in the range of 9–12%. The share of the manufacturing and use phase for the other environmental impact categories and for each service is analogous to the GWP one. The manufacturing share is predominant in the case of services with few cycles (mFRR, RR and Black Start). For the others, the increase in the lifetime energy delivered by these batteries lowers the manufacturing impacts. The only exception is represented by the resource depletion. In fact, this category presents a negligible share of the use phase in the overall resource depletion score, with values lower or equal to 27%.

3.3. Geopolitical Domain: GRMs Analysis Results

As previously mentioned, the risk mitigating factors are the HHI, NIR, the EOL(RIR) and the SI. The first one is graphically represented in Figure 7 as a bars chart for the extraction stage of the elements under evaluation. Natural Graphite has the higher HHI, equal to 0.46. This is due to China's high share global of production, equal to 67% (average in the period 2016–2020). Lithium and Aluminium have instead two HHI, respectively, equal to 0.36 and 0.33. The first Lithium producer is Australia, with a share of 56%. For Aluminium, China has a leading role in production, with a share equal to 56%. Furthermore, phosphorous has a HHI at the mining stage (in which the phosphorous is in the form of phosphate rock) equal to 0.22. As in the case of aluminium and natural graphite, China is the largest producer, with a share of total production equal to 44%.

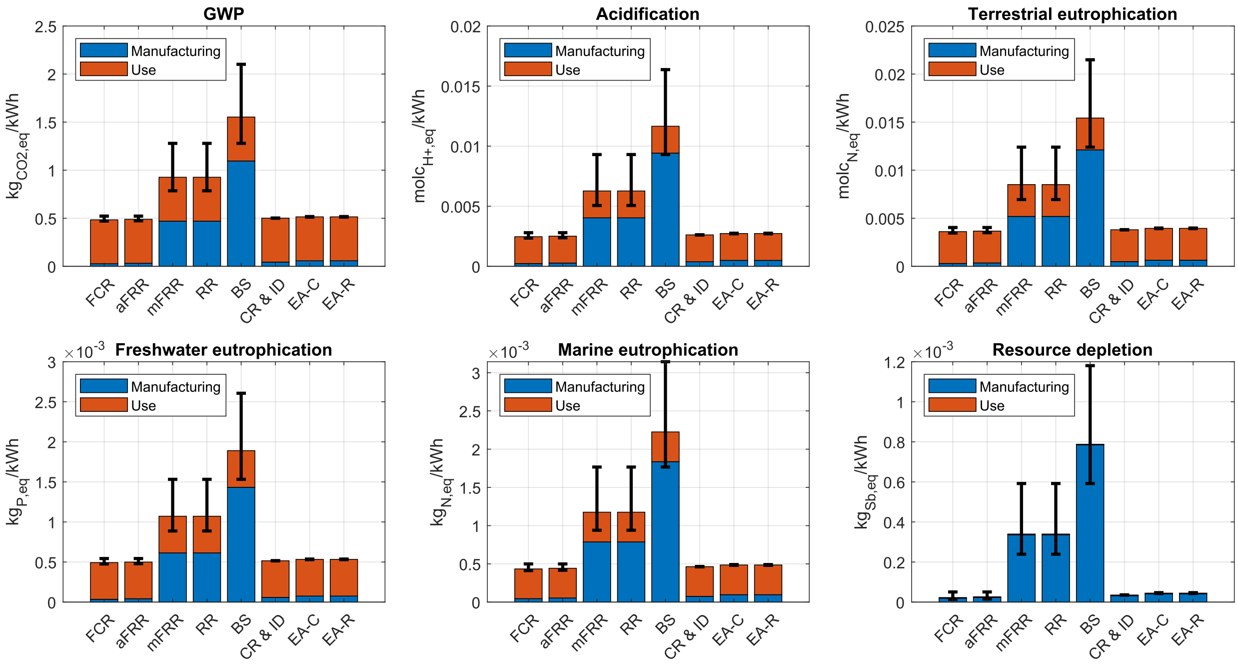

Figure 6. Breakdown of environmental impacts for Scenario C.

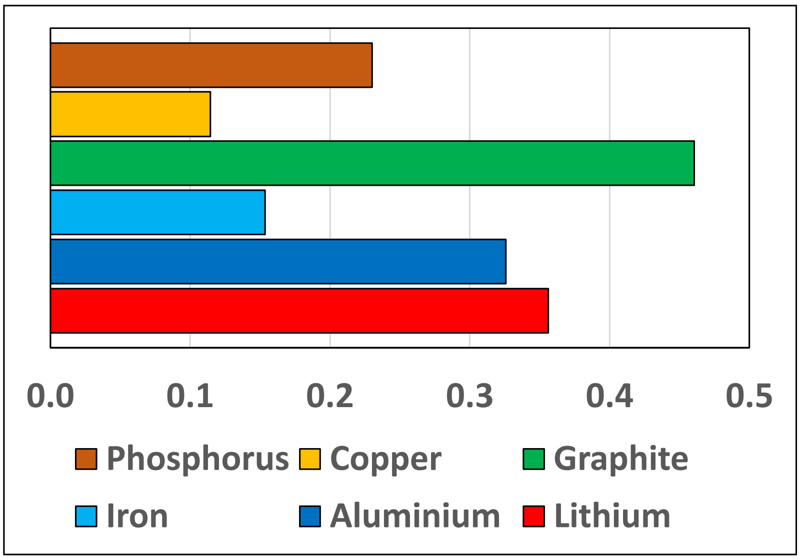

Figure 7. Bar chart of HHI for the elements under evaluation.

Table 9 reports the other risk mitigating factors. The NIR is 100% for refined Phosphorous and Lithium and almost total for Graphite (98%). It is instead slightly lower for Iron (72%). Aluminium and Copper have instead lower NIR values, respectively, equal to 59% and 44%. The value of the end-of-life recycling rate is quite high for Iron 31.5%, and lower for Aluminium (12.3%) and Copper (16.9%). For Graphite and Lithium, these values are almost negligible. Finally, the highest values of the Substitution Index are related to Graphite and Phosphorous, with values equal to 100%.

Table 9. Geopolitical risk-mitigating factors.

Element	NIR (%)	EOL_{RIR} (%)	SI (%)
Aluminium	59	12.3	80
Copper	44	16.9	90
Graphite	98	3	100
Iron	72	31.5	90
Lithium	100	≈0	90
Phosphorus	100	0	100

The supply risk CFs and the specific quantities of deployed elements are reported in Table 10, as well as the specific risks and their contribution to the final score. The supply risk is scaled to the kWh of the battery energy capacity. Natural Graphite and Phosphorus report the highest absolute score, with values equal to 0.23 and 0.18 kg/kWh, respectively. In fact, their relative contribution to the overall risk is equal to 78%. The other elements instead have a lower contribution to the total risk, since both quantities and supply risk are lower than Graphite and Phosphorus. Particularly, Aluminium, Copper, Iron and Lithium represent 8%, 4%, 7% and 3% of the overall risk quota, respectively. The small value of Lithium (0.02 kg/kWh) compared to the others is determined by the smallest quantity of the selected elements (0.12 kg/kWh), although it represent the third higher value in terms of supply risk (0.16), after Phosphorus (0.35) and Natural Graphite (0.23).

Table 10. Breakdown of specific quantities and supply risks.

Element	Supply Risk CF (-)	Quantity ($kg/kWh_{en,cap}$)	Risk ($kg/kWh_{en,cap}$)	Risk Contribution (%)
Aluminium	0.06	0.82	0.05	8
Copper	0.03	0.91	0.03	4
Graphite	0.23	1.36	0.23	50
Iron	0.05	0.91	0.05	7
Lithium	0.16	0.12	0.02	3
Phosphorus	0.35	0.51	0.18	28
Total	-	4.63	0.63	100

Furthermore, quantitative risks, expressed in kg/kWh of electricity delivered throughout the system's useful life, are reported in Table 11 for each scenario and service. As for economic and environmental assessment, the type of service has a fundamental role in determining the supply risk score. Indeed, services characterised by a higher number of cycles (i.e., FCR and aFRR) have the lowest supply risk scores. For Scenario E, supply risk scores of FCR and aFRR are, respectively, equal to 7.69×10^{-5} and 9.23×10^{-5} kg/kWh. Higher values are reported by services featured by a low number of cycles, such as mFRR, RR and Black Start. In detail, supply risk scores of mFRR and RR range between 1.85×10^{-3} and 4.61×10^{-3} kg/kWh, while Black Start values range between 4.61×10^{-3} and 9.23×10^{-3} kg/kWh. Finally, intermediate values are assumed by Arbitrage and CR and ID services, with values within 2.43×10^{-4}–3.42×10^{-4} kg/kWh.

Table 11. Overall supply risk of LFP battery for each service and for each scenario, expressed in $kg/kWh_{en,del}$.

Service	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
FCR	3.69×10^{-4}	1.45×10^{-4}	1.51×10^{-4}	1.02×10^{-4}	7.69×10^{-5}
aFRR	3.69×10^{-4}	1.72×10^{-4}	1.80×10^{-4}	1.22×10^{-4}	9.23×10^{-5}
mFRR	4.61×10^{-3}	3.36×10^{-3}	2.64×10^{-3}	2.17×10^{-3}	1.85×10^{-3}
RR	4.61×10^{-3}	3.36×10^{-3}	2.64×10^{-3}	2.17×10^{-3}	1.85×10^{-3}
Black Start	9.23×10^{-3}	7.38×10^{-3}	6.15×10^{-3}	5.27×10^{-3}	4.61×10^{-3}
CR & ID	2.56×10^{-4}	2.53×10^{-4}	2.53×10^{-4}	2.46×10^{-4}	2.43×10^{-4}
Arbitrage-Commercial	3.42×10^{-4}	3.33×10^{-4}	3.24×10^{-4}	3.16×10^{-4}	3.08×10^{-4}
Arbitrage-Residential	3.42×10^{-4}	3.33×10^{-4}	3.24×10^{-4}	3.16×10^{-4}	3.08×10^{-4}

3.4. Sensitivity Analysis

As previously mentioned, a sensitivity analysis is carried out for accounting the effect of final results linked to the reduced cycle life and round-trip efficiency of batteries in the case of low discharge duration. Indeed, low values increase the stress on electrodes due to a fast volume change [53]. Moreover, the discharge efficiency is also reduced. To account for these phenomena, different values were exploited compared to the average ones reported in Table 4. In detail, the cycle life is equal to 2500 cycles and the discharge efficiency is equal to 92% for frequency-based services (i.e., FCR, aFRR and mFRR). A range of cycle life and discharge efficiencies are accounted instead of RR, due to the variability of discharge duration from 0.25 h to 1 h. An overview of the assumptions made for the RR service is reported in Table 12.

Table 12. Cycle life expectancy and discharge efficiency considered for the sensitivity analysis of the RR service.

Parameter	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
κ_c	2500	3125	3750	4375	5000
$\eta_{DC}^{(dch)}$	92%	93.5%	95%	96.5%	98%

The obtained economic results, according to the assumptions listed in Table 12, are reported in Table 13. In detail, the FCR and aFRR range between 1.04×10^2 €/MWh and 1.37×10^3 €/MWh. Regarding instead the mFRR, the LCOS ranges between 6.19×10^3 €/MWh and 1.54×10^4 €/MWh. Finally, the LCOS for RR ranges between 2.27×10^3 €/MWh and 1.54×10^4 €/MWh. Results for the other services remain unchanged since they are not affected by the parametric analysis. It can be seen how, despite the slightly higher values for LCOS in frequency-based services, relative results and considerations about different electricity services are still the same.

Table 13. Results of LCOS (in EUR/MWh) in the sensitivity analysis.

Service	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
FCR	1373.4	233.9	149.4	119.7	104.5
aFRR	1373.4	266.6	167.3	132	113.9
mFRR	15,405.1	11,219.4	8827.6	7280	6196.6
RR	15,405.1	7180.7	4371.3	3032.6	2273.8
Black start	11,152.1	8932.5	7452.8	6395.9	5603.2
CR and ID	280.5	242.7	226.5	216.9	210.3
Arbitrage-Commercial	766.1	560.9	514.6	489.4	471.3
Arbitrage-Residential	1307.8	889.8	799.9	753.0	720.6

The environmental impacts of FCR, aFRR, mFRR and RR slightly increase as well, compared to the base case. A graphical overview of the modification in the results due to the sensitivity analysis is reported in Figure 8. In detail, there is an increase in the GWP value of services FCR and aFRR for Scenario A of around 15%. The increase in GWP values for the mFRR and RR are instead lower, and equal to 3.9%. Similar trends are shown for the other impact categories affected by the reduction in cycle life and discharge efficiency.

Finally, in Table 14 the supply risk scores for the parametric analysis are reported. The FCR and aFRR supply risk scores range between 8.19×10^{-5} and 7.87×10^{-4} kg/kWh. The mFRR and RR values range instead between 1.85×10^{-3} kg/kWh and 4.92×10^{-3}.

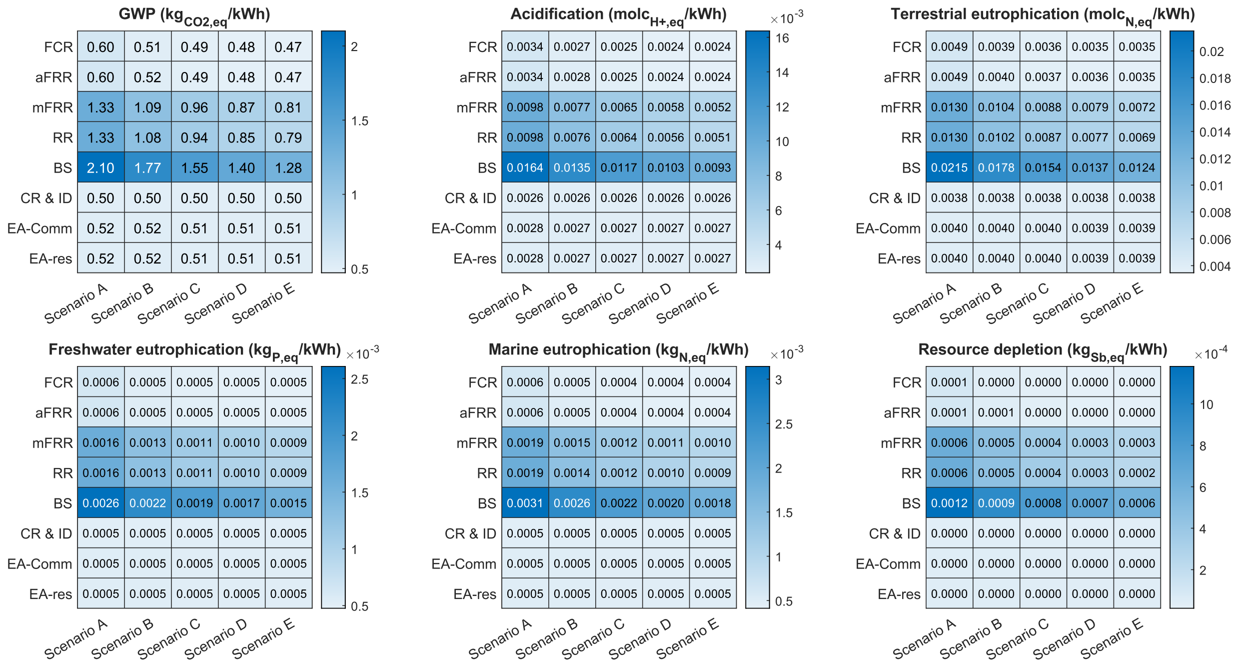

Figure 8. Environmental impacts results in the sensitivity analysis.

Table 14. Supply risk of LFP battery in the sensitivity case, expressed in $kg/kWh_{en,del}$.

Service	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
FCR	7.87×10^{-4}	3.08×10^{-4}	1.61×10^{-4}	1.08×10^{-4}	8.19×10^{-5}
aFRR	7.87×10^{-4}	3.66×10^{-4}	1.92×10^{-4}	1.30×10^{-4}	9.83×10^{-5}
mFRR	4.92×10^{-3}	3.58×10^{-3}	2.81×10^{-3}	2.31×10^{-3}	1.97×10^{-3}
RR	4.92×10^{-3}	3.52×10^{-3}	2.72×10^{-3}	2.21×10^{-3}	1.85×10^{-3}
Black Start	9.23×10^{-3}	7.38×10^{-3}	6.15×10^{-3}	5.27×10^{-3}	4.61×10^{-3}
CR & ID	2.56×10^{-4}	2.53×10^{-4}	2.53×10^{-4}	2.46×10^{-4}	2.43×10^{-4}
Arbitrage-Commercial	3.42×10^{-4}	3.33×10^{-4}	3.24×10^{-4}	3.16×10^{-4}	3.08×10^{-4}
Arbitrage-Residential	3.42×10^{-4}	3.33×10^{-4}	3.24×10^{-4}	3.16×10^{-4}	3.08×10^{-4}

3.5. Discussion

The analysis of the results for the economic, environmental and geopolitical domains shows that the impacts of the battery plants decrease with the increase in the charge/discharge cycles provided throughout the operating lifetime. This is true also in the case of the provision of services that require battery stack replacement during the operation of the battery plants (i.e., FCR and aFRR). The outcomes of the analysis are presented in Table 15 in terms of the best service to provide for Li-ion batteries in order to minimise the impacts for each domain. In detail, for Scenario A, the best service is represented by CR and ID for all the domains considered. Scenario B differs from Scenario A for the best service to provide in order to minimise the economic impact, namely FCR. For all the other scenarios (i.e., Scenario C, Scenario D and Scenario E), the best service is FCR for all three domains.

Table 15. Best services to provide for Li-ion batteries for each domain and scenario considered.

Domain	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
Economic	CR & ID	FCR	FCR	FCR	FCR
Environmental	CR & ID	CR & ID	FCR	FCR	FCR
Geopolitical	CR & ID	CR & ID	FCR	FCR	FCR

4. Conclusions

This paper presented a multidisciplinary approach for the characterization of Li-ion batteries according to three analysis domains, namely economic, environmental and geopolitical ones. While the first two domains are represented by Life Cycle Costing and environmental LCA, the latter one is described through an indicator that measures the risk of supply with reference to the materials used in the battery manufacturing. The multidisciplinary approach has been applied to a Lithium Iron Phosphate battery case study, and a parametric analysis has been carried out according to the main features of the electricity services. The analysis showed that, with reference to the considered scenarios, the "Frequency Containment Reserve" and the "Congestion Relief and Investment Deferral" results are the services better fitting with the indicators developed to cover the three analysis domains, even though the "Frequency Containment Reserve" results overcome the "Congestion Relief and Investment Deferral" in a higher number of scenarios. The developed approach can hence help decision makers in choosing among different energy storage technologies (ESTs) during the planning stages by considering all the electric services that these technologies can provide. Usually, EST assessment is performed by considering economic aspects, environmental impact and supply chain risk in an isolated way, neglecting the complexity of the interactions of the different domains and and the trade-offs among the criteria. However, decision makers need a coherent and exhaustive framework for the evaluation of ESTs. This approach can be extended to other ESTs, obtaining in this way a fair comparison between them. This is due to the fact that this methodology takes into account not only economic, environmental and supply risk features, but also the technical aspects through the functional unit at which results are normalised. Further evaluation will be carried out in order to analyse further domains (e.g., social life cycle assessment), as well as to compare different ESTs according to the proposed impact categories. Moreover, geopolitical risk analysis will be extended to other manufacturing stages to provide an overall vision of the supply chain and the potential threats to be overcome to enable the use of these technologies.

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Abbreviations

The following abbreviations are used in this manuscript:

ACD	Acidification
aFRR	authomatic Frequency Restoration Reserve
BMS	Battery Management System
BS	Black Start
CD & ID	Congestion Relief and Investment Deferral
EA	Energy Arbitrage
eLCA	environmental Life Cycle Assessment
EoL-RIR	End of Life Recycling Input Rate
EST	Energy Storage Technology

FCR	Frequency Containment Reserve
FE	Freshwater Eutrophication
GWP	Global Warming Potential
HHI	Herfindahl–Hirschman Index
LCOS	Levelised Cost of Storage
LFP Li-ion	lithium iron phosphate lithium-ion battery type
ME	Marine Eutrophication
mFRR	manual Frequency Restoration Reserve
O&M	Operation and Maintenance
RR	Replacement Reserve
NIR	Net Import Reliance
TE	Terrestrial Eutrophication
TLCC	Total Life Cycle Cost
WACC	Weighted Average Cost of Capital

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