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Comparative life cycle assessment of two different battery technologies: lithium iron phosphate and sodium-sulfur

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Abstract

The generation, storage and use of electric energy is a relevant issue for the modern society that is dependent from this energy typology for its activities (e.g. heating, goods production). Batteries are key components for the storage of electric energy, to be used for a large set of domestic, industrial and transport applications. The paper investigates the environmental impacts of two different battery technologies used as accumulator in the context of a production plant: (i) the lithium iron phosphate (LiFePO4) battery, and (ii) the sodium-sulfur (NaS) battery. The analyses have been performed according to the Life Cycle Assessment methodology, by using the ReCiPe method at midpoint and endpoint levels to quantify the potential environmental impacts. Results highlight the principal impact of two different technologies, considering all environmental indicators. Results show that the LiFePO4 solution can be considered the most sustainable solution for the considered industrial application. However, the difference is very small, within 2% and strongly influenced by the energy needed to recharge the batteries during the use phase. Instead, if we consider the production of batteries, the NaS solution resulted the most sustainable solution with an impact in terms of the aggregated single score damage category of about a half in comparison with the LiFePO4 solution.

Keywords: batteries; lithium iron phosphate; sodium-sulfur; life cycle assessment

1. Introduction

The increasing energy needs and the depleting nature of non-renewable resources require the use of renewable sources and sustainable energy storage technologies [1].

Renewable energy sources, such as sun and wind, are essential for an environmentally sustainable future. Strict environmental regulations and action plans for the transition to a decarbonized and more sustainable economy are increasingly used worldwide. For example, the Italian Integrated National Energy and Climate Plan (INECP) set national targets for energy efficiency, use of renewables and reduction of CO_2 emissions to be satisfied by 2030. The Plan is structured in lines of action from decarbonization to energy efficiency, through the development of the internal energy market, research, innovation and competitiveness [2]. However, renewable energy sources are sometimes inconstant, because their availability may depend on climatic factors and weather phenomena that cannot be controlled or predicted with accuracy. Battery storage systems are the smartest solution to increase system flexibility [3].

The battery convert chemical energy into electrical energy [4]. Its ability to rapidly absorb, retain and then feed electricity back into the grid makes it the key element for a successful energy transition. Most current research focuses on batteries used in electric vehicles [5]. However, recent deployments of batteries as a grid-connected energy storage system are developing, with lithium-ion batteries as the dominant technology for this application. The growing importance of lithium-ion batteries for residential and industrial energy storage triggered the need for a comparison in terms of the potential environmental impacts of the different battery typologies in use [6].

The sodium sulfur battery (NaS) is another technology currently used for grid energy storage. The NaS batteries have good specific energy, high efficiency and excellent cycle life, characteristics that make them the ideal choice for stationary energy storage. On the other hand, its implementation for non-

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stationary applications in electric vehicles is not recommended due to safety issues about molten sodium and highly corrosive sodium polysulphide on-board vehicles. Additionally, they require energy to keep them at operating temperature (ca 300°C), so this battery technology is more suitable in stationary solutions [7]. Stationary storage batteries can be used for a range of applications: a recent study assessed the potential for battery storage [8] to replace combined cycle gas turbine (CCGT) plants in meeting variable peak demand for current and future energy scenarios in the United Kingdom.

The energy transition can be considered green and environmentally friendly, only if it is guaranteed that the life cycles of products and equipment to be used are green and ecological. In this context, the Life Cycle Assessment (LCA) method can be considered the most appropriate and widespread technique to assess a product life cycle from the environmental point of view. LCA allows to analyze and evaluate the resources and environmental impacts associated with all stages of a product's life including raw materials, the manufacturing process, packaging, energy and other human activities [9]. Through modelling the different stages of the system life cycle of storage, production, use and end-of-life, it is possible to quantify damages and impacts and inform where and when they occur [10]. Vandepaer et al. [11] used LCA to analyze the environmental impact of lithium batteries and compared stationary lithium metal polymer (LMP) batteries with lithium-ion batteries. The literature contains many studies that investigate the environmental impacts of batteries for electric vehicle applications, while few studies examine their environmental performance in stationary applications. Recently, an Italian study has been carried out with the aim of evaluating the sustainability of stationary storage systems within an Italian scenario of production and use. Within this study a life cycle assessment analysis has been performed for three different batteries produced by an Italian manufacturer: lithium iron phosphate (LiFePO4), nickel–manganese–cobalt (NMC) 532, and NMC 622) [3].

The present paper aims to expand the literature on such topics, by investigating the environmental impacts of two different battery technologies used in the context of a stationary application as accumulator in a production plant: (i) the LiFePO4 battery, and (ii) the NaS battery. The study has been realized by applying the LCA methodology which allowed to quantify the environmental impacts generated from the different technologies by using the ReCiPe impact assessment method, at both the midpoint and endpoint levels.

After this Introduction the paper is structured as follows. Section 2 briefly describes the main characteristics of the considered battery technologies. Section 3 details the comparative LCA study and reports the obtained results. Finally, Section 4 concludes the paper and proposes some future developments.

2. Materials and methods

For understanding the environmental impact of a different battery technologies two type of battery, with a difference technology has been considerate in the case study. An overview of the production of many of the materials in these batteries has been presented by Gaines et al. [12] and Gaines and Singh [13]. Also, a good discussion of the processes required to make battery materials can be found in the EVTECA report [14], which includes a few flow diagrams and some rolled-up data. However, there is a considerable variation in properties within battery technologies, due to a combination of factors including advances in chemistry, manufacturing, and a different application, intended for power or energy applications. Furthermore, it is not always clear whether a cited value is based on a kg of cells or battery. Batteries are comprised of more than just cells; other included items are conductors, packaging, insulators, circuit board controllers, and in the case of large cell assemblies, cooling systems, etc. The Li-ion batteries represent one of a new technology with a high energy density and cycle life and no memory effect. The most common application for these batteries is in the context of electronic products, such as cell phones, hearing aids, computers, and the like, electric vehicle and plugin, electric vehicle applications and Electric Power System (EPS) [15]. The composition of Li-ion batteries can be quite variable, depending primarily on the composition of the cathode. Lithium-iron-phosphate batteries are commonly used in energy power supply owing to their safety performance and long-life cycling capability.

The sodium sulfur battery possesses excellent energy and power density, high electrical efficiency, long life, a small footprint, pulse power capability, instantaneous response, and reliable operation making it an excellent candidate for Electric Power System (EPS) application. Modules have a pulse power capability up to five times their continuous rating (for 30 seconds) that is limited by the cell temperature rise, internal resistance, and depth of discharge. Attractive features of this battery typology include: (i) the NAS batteries deliver about three times more energy per unit volume than lead acid batteries; (ii) the factor per unit weight is almost 10; (iii) the NAS battery is designed to last 15 years, through 2,500 full charge-discharge cycles. Sulfur is used as an active material at the positive electrode, while sodium is used at the negative electrode. Electrodes are separated by a sodium-ion-conductive ceramic solid electrolyte. High temperature keeps the electrode active materials in a liquid state while the electrolyte is solid. These conditions reduce resistance and enable efficient battery performance, averaged over lifetime discharge. NaS batteries have good specific energy and cycle life and are currently being used in Japan and the US for grid energy storage. For this battery, the electrodes are liquids, and the electrolyte is a solid, whereas for the other batteries, the electrodes are solids, and the electrolyte is liquid.

2.1. Life Cycle Assessment (LCA) methodology

This study has been carried by following the Life Cycle Assessment methodology (ISO 14040-14044) that allows to analyze a product, process, service or activity over its entire life cycle and to quantify the relative impacts on the

environment. LCA analyses all the interaction between the environment and the activities needed for the realization of a product in a holistic way, considering several criteria that evaluate all the possible categories of environmental impacts and damages that may result from the processes (ISO UNIEN, 2011, ISO UNIEN, 2010). According to the above-mentioned standards, the LCA studies must include four phases:
1) Goal and scope definition: in this phase the objective, the functional unit, and the system boundaries must be clearly defined; 2) Inventory analysis phase or Life Cycle Inventory (LCI): consists in the compilation and quantification of the inputs and outputs of all the activities within the system boundaries that have relevant environmental impacts. This is a key phase of an LCA study in which the system under analysis is subdivided in unitary processes; 3) Impact assessment phase of Life Cycle Impact Assessment (LCIA): the data gathered in the LCI phase are translated into potential environmental impacts by means of characterization and weighting factors. Multiple impact indicators can be utilized to guarantee a complete vision of the environmental effects of the study target; 4) Interpretation of the results: the study is evaluated considering completeness, sensitivity, and consistency. Lastly, conclusion, limitations and recommendation are made, to improve the environmental behavior of the process studied. Among the several possible advantages of LCA, it helps to improve the environmental performances of products and processes during their development stages, identifying critical issues and improved efficiency opportunities. It is an iterative technique so, as data and new information are acquired or the process development advances, various aspects of the analysis can be changed and replaced. The software SimaPro 8.0.5.13 has been used to carry out the analysis.

3. Case study

In order to compare the environmental impacts of the two different technologies of electrochemical storage, an Italian case study was considered. The lithium ion and NaS batteries are manufactured and supplied by an Italian company and each one has the capacity to provide 1000 kWh of dc energy at 50kW rated. The batteries also have the capability to provide 5 times the rated power for a short time, up to 30 seconds, and peak shaving. The nominal operating voltage of the batteries is 700Vdc. The chosen use profile is based on the requirements of a manufacturing company located in the center of Italy, which needs 5 charge-discharge cycles during one working day. Considering the different max life of each technology, to cover the considered lifetime (i.e. 20 years), 4 lithium ion batteries and 5 NaS batteries are necessary. Table 1 lists some key properties of the battery technologies [16].

Table 1. Electric Power System proprieties

Battery technologies	**LiFePo4**	**NaS**
Density [Wh/kg]	130	150
Voltage single cell [V]	3,25	2,7
Total Energy [kWh]	1000	1000
Eff [%]	98	92
Max Cycle	6000	4500
Max Life [years]	5	4
Battery total Mass [kg]	7692	6667

3.1. Goal and scope definition

The present LCA study aims at evaluating and comparing the environmental performances of two different battery technologies used as accumulators for static applications in an Italian industrial scenario.

The chosen functional unit is represented by "the manufacturing and use as static accumulator in an Italian industrial application of a battery, able to provide 1000 kWh of dc energy for a lifetime of 20 years".

The system boundaries include the manufacturing of the batteries and their charges during the use phase. Transport phases, as well as batteries end of life are considered out of scope of the present analysis.

3.2. Life cycle inventory

In order to produce as accurate as possible life cycle inventories (LCI), an extensive research on the state of the art of the selected technologies has been performed. An extensive analysis on commercially available and implemented solutions has been also made in order to complete and enhance the final dimensioning of the storage system [17]–[20].

LCI is a basic activity to assess the impact of the life cycle, allowing to quantify the flows into and out of the system boundaries. These flows include the use of resources (raw materials, energy for battery manufacturing and use phase). The primary data for process were collected at the company production site. The secondary data, instead, were extrapolated from the updated literature and from the Ecoinvent databases [21]. The main material, resources and energy consumption related to the manufacturing and use phases, and calculated according to the chosen functional unit, are shown in Table 2 and Table 3 for the LiFePO4 and NaS batteries, respectively [16].

Table 2. Life cycle inventory of lithium iron phosphate battery

Component	**Material**	**Percentage composition [%]**	**Quantity**	**Unit**
Cathodes	Lithium	36	2769	kg
Anodes	Graphite, Copper	31	2385	kg
Electrolyte	(LiPF6)	11	846	kg
Separator	Polypropylene	2	154	kg
Case	Steel	20	1538	kg
Total		100	7692	kg
Energy material Production	Energy		915385	MJ
Energy use phase	Energy		22449	MWh

Table 3. Life cycle inventory of NaS battery

Component	Material	Percentage composition [%]	Quantity	Unit
Cathodes	Sulfur	12,5	833	kg
Anodes	Sodium	8	533	kg
Electrolyte	α, β Alumina	12,5	833	kg
Separator	Polypropylene	8	533	kg
Case	Steel	39,5	2633	kg
Safety system.	Miscellaneous	19,5	1300	kg
Tot		100	6666	kg
Energy Material Production	Energy		786667	MJ
Energy use phase	Energy		23913	MWh

3.3. Results and discussion

The Life Cycle Impact Assessment (LCIA) has been realized with the support of the SimaPro 8.0.5.13 software tool, equipped with the Ecoinvent 3.1 database. Results have been calculated by using the ReCiPe impact assessment methods, considering both the 18 midpoint categories (ReCiPe mid-point - Hierarchist (H) version – Europe) and the Single Score endpoint indicator (ReCiPe end-point - Hierarchist (H) version - Europe with the average weighting set (A)) [22]. All these results allow to have a global overview about the causes of environmental impacts.

The first comparison has been made in terms of the 18 ReCiPe midpoints: (i) Climate change (CC), (ii) Ozone depletion (OD), (iii) Terrestrial acidification (TA), (iv) Freshwater eutrophication (FE), (v) Marine eutrophication (ME), (vi) Human toxicity (HT), (vii) Photochemical oxidant formation (POF), (viii) Particulate matter formation (PMF), (ix) Terrestrial ecotoxicity (MEP), (x) Freshwater ecotoxicity (FET), (xi) Marine ecotoxicity (MET), (xii) Ionising radiation (IR), (xiii) Agricultural land occupation (ALO), (xiv) Urban land occupation (ULO), (xv) Natural land transformation (NLT), (xvi) Water depletion (WD), (xvii) Metal resource depletion (MRD), (xviii) Fossil fuel depletion (FD). Table 4 reports the split of contributions for the most important life cycle phases for each scenario and for each indicator. Green and red cells identify the most and the less sustainable solutions for each indicator, respectively. Globally analyzing the obtained results, a general consideration can be derived: the most critical item of the life cycle is the use phase with its huge consumption of electric energy needed to charge the batteries with contributions larger than the others of at least one order of magnitude, in each impact category.

For most of the ReCiPe midpoint impact categories, the LiFePO4 battery can be considered the most sustainable alternative in the context of the analyzed industrial scenario. Exceptions have been observed for the midpoint indicators TA, POF, PMF and ULO for which the NaS battery has an impact of -8,5%, -4,7%, -8,8% and -12,1% in comparison with the LiFePO4 solution, respectively. Such results are mainly due to the relevant impacts caused by the LiFePO4 battery manufacturing (4 batteries to cover a life cycle of 20 years), which is heavily affected to the energy consumed for materials and components production which are realized in China (thus by using energy generated through a Chinese energy mix).

The main difference among the two compared solutions has been observed for the MRD indicator, for which the NaS scenario has an impact of 3,86E+05 kg Fe eq, while the LiFePO4 scenario has an impact of 3,06E+05 kg Fe eq (about -26,1%). Other than for the use phase (2,62E+05 kg Fe eq vs 2,79E+05 kg Fe eq), the main differences for this category have been observed for the contributions of the battery Case, for which the NaS impact is more than double the LiFePO4 impact (1,68E+04 kg Fe eq vs 4,49E+03 kg Fe eq). This result is not surprising since the NaS case is heavier than the LiFePO4 case (2633 kg of steel vs 1538 kg of steel for each battery). Another not negligible difference has been observed in the Separator (3,22E+00 kg Fe eq vs 9,30E-01 kg Fe eq).

Table 4. Comparison among batteries life cycle in terms of ReCiPe midpoint and split of contributions for the main phases

	LiFePO4				NaS			
Impact Category	Materials	Manufacturing	Use	Life Cycle 4 batteries 20 years	Materials	Manufacturing	Use	Life Cycle 5 batteries 20 years
CC [kg CO2 eq]	6,59E+04	4,91E+05	1,36E+07	1,58E+07	1,82E+04	2,64E+05	1,45E+07	1,59E+07
OD [kg CFC-11 eq]	5,86E-03	3,05E-03	1,86E+00	1,90E+00	4,22E-03	2,00E-02	1,98E+00	2,10E+00
TA [kg SO2 eq]	4,00E+02	4,23E+03	5,26E+04	7,12E+04	1,81E+02	1,64E+03	5,61E+04	6,52E+04
FE [kg P eq]	3,21E+01	6,40E+01	2,12E+03	2,50E+03	2,58E+01	3,86E+01	2,26E+03	2,58E+03
ME [kg N eq]	1,18E+02	8,47E+01	8,93E+04	9,01E+04	6,49E+01	9,00E+02	9,51E+04	1,00E+05
HT [kg 1,4-DB eq]	2,82E+04	6,54E+04	1,81E+06	2,19E+06	4,99E+04	3,71E+04	1,93E+06	2,36E+06
POF [kg NMVOC]	2,50E+02	1,85E+03	3,14E+04	3,98E+04	1,00E+02	7,98E+02	3,35E+04	3,80E+04
PMF [kg PM10 eq]	1,77E+02	1,32E+03	1,67E+04	2,27E+04	7,02E+01	5,13E+02	1,77E+04	2,07E+04
TET [kg 1,4-DB eq]	1,04E+01	1,01E+01	8,19E+02	9,01E+02	4,80E+00	1,14E+01	8,73E+02	9,54E+02
FET [kg 1,4-DB eq]	9,55E+02	2,43E+03	6,06E+04	7,41E+04	1,04E+03	1,81E+03	6,45E+04	7,88E+04
MET [kg 1,4-DB eq]	8,90E+02	2,26E+03	5,40E+04	6,67E+04	1,06E+03	1,63E+03	5,76E+04	7,10E+04
IR [kBq U235 eq]	1,43E+04	1,28E+04	2,35E+06	2,46E+06	2,24E+03	2,68E+04	2,50E+06	2,65E+06

ALO [m2a]	2,95E+03	7,08E+03	4,81E+05	5,21E+05	1,49E+03	7,28E+03	5,13E+05	5,57E+05
ULO [m2a]	1,02E+03	3,90E+03	4,54E+04	6,51E+04	2,93E+02	1,48E+03	4,83E+04	5,72E+04
NLT [m2]	1,10E+01	2,65E+01	2,17E+03	2,32E+03	3,47E+00	2,87E+01	2,32E+03	2,48E+03
WD [m3]	8,16E+02	2,22E+03	9,38E+04	1,06E+05	1,83E+02	1,51E+03	9,99E+04	1,08E+05
MRD [kg Fe eq]	7,09E+03	4,08E+03	2,62E+05	3,06E+05	1,71E+04	4,48E+03	2,79E+05	3,86E+05
FD [kg oil eq]	1,90E+04	9,30E+04	4,21E+06	4,66E+06	6,40E+03	6,61E+04	4,48E+06	4,85E+06

Analyzing the considered scenarios at endpoint level, the obtained results are shown in Figure 1 which reports a graphical comparison among the LiFePO4 and the NaS life cycles in terms of ReCiPe endpoint Single Score, with the related split of contributions for the three ReCiPe damage categories (Human Health, Ecosystems and Resources). Results show that the LiFePO4 solution can be considered the most sustainable solution for the considered industrial application. However, the difference among the two solutions is only 1,5% (1,40E+03 kPt vs 1,43E+03 kPt) and strongly influenced by the energy needed to recharge the batteries during the use phase. This leads to the fact that the NaS batteries, which are less efficient than the LiFePO4 batteries (see Table 1), consume more electric energy, and thus cause higher environmental impacts. Regarding the split of contributions, the most important damage categories for both the solutions are the Human Health and the Resources that together represent almost the 78% of the total endpoint impacts.

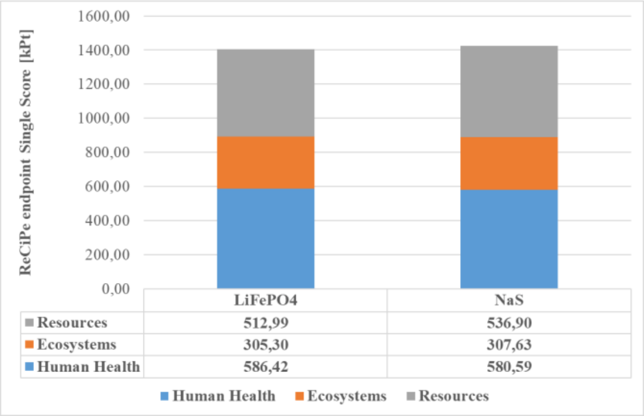
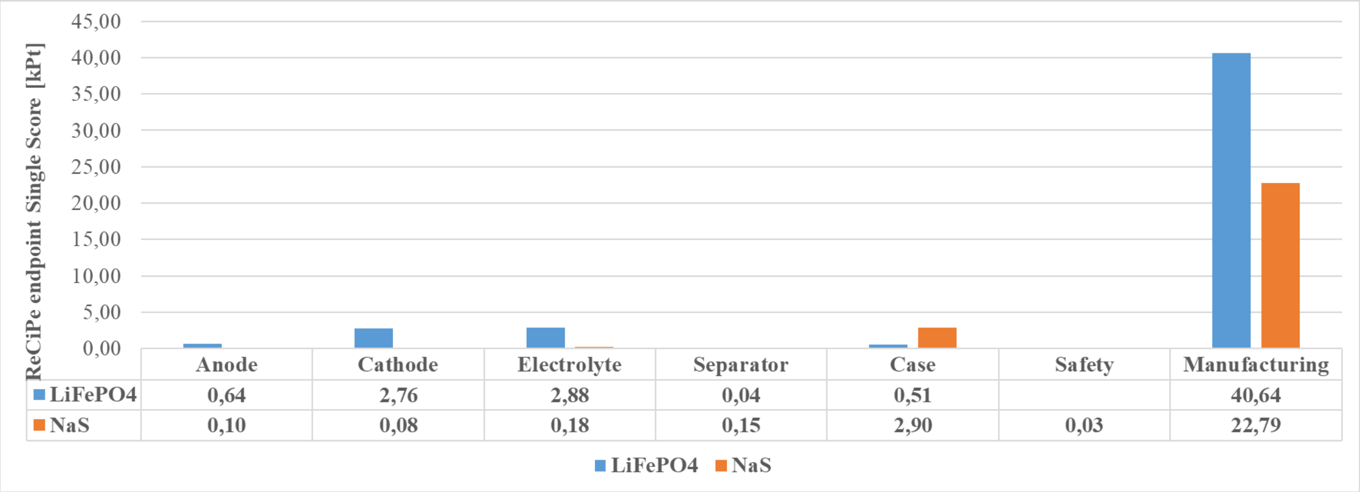


Figure 1. Comparison among batteries life cycle in terms of ReCiPe endpoint Single Score

More specifically, for the Human Health the NaS battery has less impacts than the LiFePO4 battery, due to the dangerous (for humans) materials used to manufacture this latter. For the other two damage categories the LiFePO4 battery resulted to be the most sustainable solution.

The last analysis carried out regards a comparison at endpoint level among the two battery technologies, by only considering the materials and manufacturing phases. Figure 2 reports a comparison among the main contributions for both the battery typologies, considering the ReCiPe endpoint Single Score indicator. It is worth to notice that analyzing the manufacturing of a single battery, the most sustainable solution is the NaS battery. Such result is strongly influenced by the fact that the manufacturing (modelled according to the data reported in Table 2 and Table 3) is the most critical phase, representing about 86% and 87% of the total for the LiFePO4 and NaS batteries, respectively. Given that the impact of the LiFePO4 manufacturing is almost the double of the impact of the NaS manufacturing, this latter solution obviously results more environmentally friendly than the other one. For the LiFePO4 battery also the Cathode (made of lithium) and the Electrolyte (made of lithium salts) contributes with not negligible impacts, much larger values than the same components in the NaS battery (made of sulfur and alumina, respectively). For only three components the NaS battery has a higher impact: (i) Safety system, (ii) Separator, and (iii) Case. Regarding the first component, it is only present in the NaS battery. The second one, instead, contributes with a negligible impacts to the total for both the solutions; thus, even if the Separator for a NaS battery impacts about four times the Separator of a LiFePO4 battery (same material but different weight, see Table 2 and Table 3), this difference is not relevant for the total impacts. Finally, for the third component the difference is more significant, and this is due to the higher quantity of steel used to realize the NaS battery Case, as previously observed with the midpoint analysis.



	Anode	Cathode	Electrolyte	Separator	Case	Safety	Manufacturing
■ LiFePO4	0,64	2,76	2,88	0,04	0,51		40,64
■ NaS	0,10	0,08	0,18	0,15	2,90	0,03	22,79

Figure 2. Split of contributions in terms of ReCiPe endpoint Single Score for the manufacturing of one battery

4. Conclusions

A comparative environmental LCA of LiFePO4 and NaS batteries was carried out considering their use as accumulators for static applications in an Italian industrial scenario. The two battery technologies considered are the most widespread thanks to their performance, useful life and high energy density. From the results obtained, it is not possible to identify whether one battery is absolutely the most sustainable. According to the considered indicators it is possible to derive different considerations. This is because two very efficient and usable storage systems were compared. Based on the functional unit chosen, the lifetime considered and the use profile, 4 batteries with lithium technology and 5 batteries with NaS technology are required. Furthermore, lithium cathode storage systems have a very high efficiency, about 98%, minimizing energy waste. However, the materials and manufacturing of lithium batteries are more impactful than NaS batteries. All this leads to very similar results in terms of end points: the difference between the two considered storage systems is about 2%. The main advantages of NaS batteries are a high energy density, excellent performance when compared with lead-acid batteries, they have a great durability, are quite resistant and therefore safe even with little maintenance.

With a view to future developments, it could be interesting to evaluate the end of life of storage system and evaluate a possible second life applications, for a reduction of environmental impacts and costs. The cost analysis could be also a very interesting activity, considering the costs of installation, use, maintenance and disposal. In addition, it could be interesting to focus on different use scenarios, considering also mobile applications, very widespread in the last years.

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