THE MUSIC PROJECT

Materials for sUstainable
Sodium-Ion Capacitors

Deliverable 8.1 Review of available studies of supercapacitors and batteries

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Publishable summary

With the objective of achieving a two-fold increase in energy density in comparison to the supercapacitor technologies that are currently in use, the MUSIC project has taken on the challenge of developing novel materials for hybrid capacitors. The objectives of this endeavour are not only in terms of energy density but also to reduce costs and minimize or eliminate the reliance on Critical Raw Materials (CRMs). In particular, the project is centered on the creation of the Sodium-ion Capacitors (SICs), which will remove the need for lithium and replace it with sodium, which is more readily available.

The environmental and economic benefits of a new technology or innovation are the primary factors that are considered when determining its intrinsic value in comparison to other technologies that are already in the market. As a result, the project places additional emphasis on the early consideration of sustainability aspects for SICs during the development phase, with the intention of resolving any potential conflicts between goals.

Exploring second-life and recycling options, conducting a prospective Life Cycle Analysis (LCA), and integrating cost analysis (LCC) are all components of the planned research that will contribute to the sustainable development of Energy Storage Systems (ESS). With the end goal of optimizing future manufacturing processes of sodium-ion capacitors, this holistic approach aims to deepen our understanding on the technical requirements, environmental impact, economic performance, and market expectations for the new storage system. This comprehension will ultimately lead to the optimization of the manufacturing processes.

This deliverable, which is part of Work Package 8 (WP8) titled "Life Cycle Sustainability Analysis," aims to carry out an exhaustive investigation of the state-of-the-art LCA and LCC studies that are associated with the environmental impacts and cost analysis of the current energy storage options. The primary objective is to revisit and methodically analyze previous LCA and LCC investigations that have been conducted within the realm of supercapacitors. The purpose of this comprehensive review is to evaluate the overall research landscape regarding life-cycle sustainability metrics for supercapacitor technologies, as well as to synthesize the existing body of knowledge, identify methodological trends, and identify trends in methodology.

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Abbreviations

SYMBOL	SHORTNAME
ADP	Abiotic Depletion Potential
ALOP	Agricultural Land Occupation Potential
AP	Acidification Potential
Cap	Capacitor
CAES	Compressed-Air Energy Storage
CAPEX	Capital expenditure
CED	Cumulative Energy Demand
CORDIS	Community Research and Development Information Service
EoL	End of life
EP	Eutrophication Potential
ESS	Energy Storage System
EU	European Union
FC	Fuel cell
GHG	Green House Gas
GWP	Global Warming Potential
HESS	Hybrid Energy Storage System
HTP	Human Toxicity Potential
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCIs	Life Cycle Inventories
LFP	Lithium-iron Phosphate
LIB	Lithium-ion battery
LIC	Lithium-Ion Capacitors
METP	Marine Ecotoxicity Potential
NaS	Sodium-sulfur
NMC	Nickel Manganese Cobalt
NPV	Net Present Value
O&M	Operation and Maintenance
ODP	Ozone Depletion Potential

OPEX	Operational expenditure
Pb-acid	Lead-acid
RFB	Redox Flow Battery
SCs	Supercapacitors
SIC	Sodium-ion Capacitor
TCO	Total Cost of Ownership
TRL	Technology Readiness Levels
UC	Ultracapacitor
ULOP	Urban Land Occupation Potential
UPS	Uninterruptible Power Supply

1 Introduction

Within the context of the energy transition, motivated by the increased interest on renewable energy sources and the decarbonization of industry and transportation sectors, extensive efforts are being made for the development of large-scale and cost-efficient energy storage systems capable of supporting this process. In the past few decades, research has focused on designing energy storage devices characterized with high energy and power densities such as rechargeable batteries and electrochemical supercapacitors (SCs), respectively[1]. SCs, also known as ultracapacitors, have garnered attention for their high-power density, fast charge/discharge, and long-life cycle. They store energy through electrostatic double-layer capacitance or pseudocapacitance, finding use together with or in place of batteries in applications such as electromobility[2]. A hybrid system that integrates the high-power density of supercapacitors with the high energy density of lithium-ion batteries was proposed and evaluated in the early 2000´s[3]. These hybrid capacitor-battery systems, also called metal-ion capacitors (MICs), are composed of a capacitor-type electrode (activated carbon) as positive electrode to ensure high power density by adsorption/desorption charge storage mechanism and a metal-ion battery-type electrode as faradaic negative electrode to provide high energy[4]. Among metal-ion capacitors, lithium-ion capacitors (LICs) are the most developed ones up to now. Nevertheless, scarce and diminishing lithium resources have resulted in the steeply increasing cost of lithium compounds and the classification of Lithium as a critical raw material. Fortunately, the abundance and reasonable standard reduction potential of sodium (Na^+/Na=-2.7V) make it possible to construct sodium-ion capacitors (SICs)[5].

SICs are considered more sustainable due to key attributes such as the utilization of sodium, a more abundant and widely distributed resource compared to lithium, which diminishes concerns associated with resource scarcity [6]. In addition, LICs are based on lithium, which is already considered a Critical Raw Material (CRM) due to the increasing demand of lithium-ion batteries. Thus, within SIC technology, its use will be avoided. This aligns with some of the fundamental principles of sustainable development by mitigating the pressures on limited resources while promoting a more equitable distribution of raw materials. Additionally, extraction and processing of sodium is bounded to smaller environmental impacts than those of lithium and other metals[7]. In particular, lesser risks of causing detrimental effects like leaching toxic compounds into soil, water, or air, phenomena that can occur with cobalt and nickel make of sodium an attractive alternative [8]. Furthermore, the energy and power density traits of SICs play a pivotal role in contributing to their reduced environmental impact in contrast to that of LICs. Their ability to deliver rapid energy release, facilitating applications like regenerative braking, enhances energy efficiency and reduces waste[8]. This can lead to a decrease in overall energy consumption within the use phase and could contribute to lower emissions in different industrial sectors.

However, it is crucial to acknowledge that the environmental and economic benefits of SICs have to be investigated by comprehensive life cycle approaches such as the life cycle assessment (LCA) and life cycle costing (LCC) methodologies[7]. These methods consider the different life cycle stages of a product, from raw materials extraction to use phase and End-of-Life (EoL), quantifying all material and energy inputs and outputs as well as the associated costs at each stage to subsequently provide an insight of their environmental footprint and cost efficiency. Ongoing research already focuses on the minimization of any potential negative impacts associated with their development and deployment, with remaining challenges such as the selection of sustainable active materials, optimization of electrode fabrication processes, efficient recycling strategies, and electrolyte selection, which need to be continuously addressed to ensure the full realization of their environmental potential [8,9].

This deliverable is part of the WP8 "Life Cycle Sustainability Analysis" and it is also part of the Task 8.1 "Review of available studies of supercapacitors and batteries". Its primary objective is to conduct a comprehensive examination of extant Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) studies pertaining to the life-cycle energy and environmental impacts associated with supercapacitors. The overarching purpose of this deliverable is to revisit and to systematically analyze all preceding LCA and LCC investigations within the realm of supercapacitors. Through this rigorous review, our intention is to synthesize existing knowledge, identify methodological trends, and assess the overall landscape of research in the evaluation of life-cycle sustainability metrics for supercapacitor (SC) technologies.

2 Review methodology

Herein, an extensive literature review has been conducted for the identification of available studies related to the sustainability character of SCs and hybrid capacitors, in particular of those that provide a quantitative analysis of their environmental profile and cost efficiency, *i.e.* LCAs and LCCs respectively.

The search is conducted via the search engines Google Scholar, Scopus and Community Research and Development Information Service (CORDIS) for LCAs and via the search engines Google Scholar, Google and CORDIS for LCCs. The difference between the two groups lies on the fact that some economic assessments are more likely to be published on commerce-oriented platforms instead of entirely academic portals. Google Scholar and Scopus have been considered sufficient for the identification of academic literature on an international level, whereas the CORDIS platform may provide further information arising from projects funded by the European Commission and which may be presented in the form of reports instead of journal publications.

Similarly, two sets of keyword strings have been defined. For the identification of LCAs the strings ´supercapacitor AND (LCA OR environmental impacts)´, ´hybrid capacitor AND (LCA OR environmental impacts)´,´ultracapacitor AND (LCA OR environmental impacts)´, ´sodium ion capacitor AND (LCA OR environmental impacts)´ and ´lithium ion capacitor AND (LCA OR environmental impacts)´ have been used. For the case of LCCs, the keyword strings ´supercapacitor AND (LCC OR cost OR CAPEX), ´hybrid capacitor AND (LCC OR cost OR CAPEX)´, ´ultracapacitor AND (LCC OR cost OR CAPEX)´, ´sodium ion capacitor AND (LCC OR cost OR CAPEX)´ and ´lithium ion capacitor AND (LCC OR cost OR CAPEX)´ were used instead. Studies that provide a quantitative analysis of environmental impacts or cost assessment of capacitor production after the year 2000 have been considered. Studies about e-mobility or stationary power systems including a description of the production of supercapacitors have also been recorded.

The technical and technological aspects registered in each column of Table 1 and 2 are considered of most relevance for LCAs and LCCs respectively, as they provide sufficient basis for system characterization with a look on comparability. Details on type of technology, stage of development, intended application, boundaries of the model, source of data, functional unit and impact assessment method have been the base of the screening.

In the following section, a detailed analysis of the most important parameters to be considered when carrying out an LCA and LCC study is provided, starting with the study of the environmental aspects after which the economic analysis has been conducted. In the last section, some general considerations of the results and recommendations are provided.

3 Literature review results

3.1 Life cycle assessment

Our exploration into the LCA of supercapacitors unveils a significant disparity when compared to the extensive body of work dedicated to the life cycle evaluation of lithium-ion batteries. The research landscape for supercapacitors is notably constrained, primarily fixating on specific aspects, particularly the production of carbon materials for supercapacitors. Unlike the extensive literature available for lithium-ion batteries, which provides analysis on the different life cycle stages of the systems, the majority of studies on supercapacitors tend to focus on their production phases.

Furthermore, this scarcity of comprehensive LCA studies extends into the field of next-generation supercapacitors, exemplified by sodium-ion capacitors. Within this innovative category, there is a discernible dearth of readily available resources, indicating a notable gap in our understanding of the environmental implications associated with these advanced energy storage technologies. This underscores the imperative for additional exploration and in-depth life cycle assessments to foster a holistic comprehension of the environmental footprint of supercapacitors. This need becomes increasingly crucial as the technological landscape continues to evolve.

In the pursuit of a thorough understanding of the LCA landscape pertaining to supercapacitors, an extensive review of pertinent scholarly literature was meticulously undertaken. This encompassing review included a diverse selection of academic articles, reports, and other relevant publications, totalling 32 sources (**Error! Reference source not found.**). Notably, this comprehensive examination transcends traditional research publications, incorporating insights derived from projects funded by the EU's framework programmes for research and innovation.

With regards to EU projects, a total of 13 projects were identified using the previously mentioned strings and via the CORDIS portal. These projects were focused either on the development of new SC technologies or on the development of novel materials for SC applications, with attention to the sustainability profile of the technologies assessed (according to the project description). However, 10 out of the 13 projects did not provide publicly available literature regarding LCA or environmental assessments. One project (AUTOSUPERCAP) resulted in a publication already identified via the other academic portals. Another project (NETFICCIENT) provided a superficial analysis of environmental impacts from capacitors used for renewables support. One last project (HYHEELS) provided a comparative assessment of SC versus different battery systems in automotive applications.

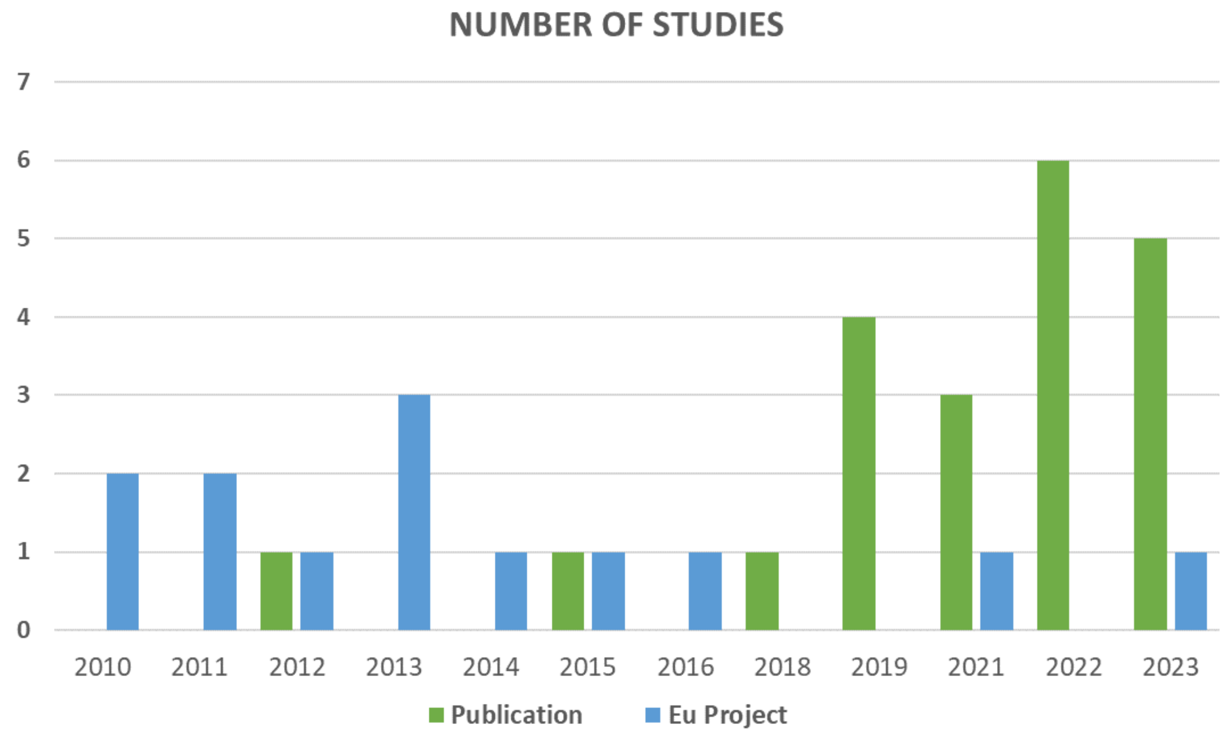

Figure 1. Number of LCA publications and EU projects per year between 2010 and 2023

3.1.1 Goal and scope

In examining the reviewed articles, it was noted that more than 80% did not explore application aspects. Instead, they predominantly focused on production of electrode materials.

Among the reviewed articles, three articles have specifically addressed the application. In 2015, Weil *et al.* conducted a LCA of supercapacitors in electric vehicles [10]. Additionally, in 2022, Hatzfeld *et al*. conducted research investigating the LCA of supercapacitors, specifically in the context of multifunctional faced [11]. Furthermore, in 2023, Mayanti assessed the life cycle of electric buses with a focus on the LFP energy storage system[12].

In evaluating the system boundaries within the reviewed articles, 8 of the studies adopted a cradle-to-gate system boundary, emphasizing the environmental impact from the extraction of raw materials to the completion of the manufacturing process. Following this, 6 articles focused on a cradle-to-grave system boundary, encompassing the entire life cycle from production to disposal. Additionally, two studies implemented a gate-to-gate system boundary, concentrating specifically on manufacturing processes without considering the broader life cycle stages. Only one article extended its system boundaries to include the use-phase, providing a more holistic perspective that considers the operational stage of supercapacitors in addition to their production and end-of-life stages. While a cradle-to-gate system boundary is common and valuable for understanding the environmental impact of manufacturing phases, it is essential to acknowledge that a complete life cycle assessment, covering the entire life cycle, provides a more holistic view of the sustainability of products.

The selection of a functional unit in the LCA of energy storage systems can vary, contingent on the study's goals, scope, and the specific characteristics of the energy storage technology under evaluation. Common functional units in the LCA of energy storage systems often include energy, capacity, cycle life, lifetime energy throughput, and the tailoring of the functional unit to the specific application of the energy storage system. Studies conducted by Cossutta *et al.*[13], Jiang *et al.*[14], Glogic *et al*.[15], and Kamali *et al.*[16]. defined the functional unit either in terms of the energy capacity of the supercapacitor or, more specifically, in terms of the employed electrode.

Moreover, based on the reviewed articles, certain studies within the field of supercapacitor assessment focused on the various materials used in the electrodes. In these studies, the functional unit was determined by the electrode material's production process. This approach provided a comprehensive evaluation from raw material extraction to the final fabrication of these critical components, recognizing the pivotal role that electrode materials play in supercapacitor performance. Meanwhile, among the reviewed articles, seven studies conducted life cycle assessments based on the functional unit of electrode material production. Table 1 provides an overview of the other functional units that are used.

3.1.2 Data sources

In LCA, data sources play a pivotal role in ensuring the reliability and robustness of study outcomes. These sources can be broadly categorized into primary and secondary data. Primary data refers to information collected directly for the specific study, such as through surveys, experiments, or observations. Within the context of LCA studies on supercapacitors, primary data might involve the direct measurement of environmental impacts associated with their production and use[17]. On the other hand, secondary data encompasses pre-existing information from sources like literature, databases, or previously conducted LCAs. Researchers often leverage secondary data to enhance the efficiency and cost-effectiveness of their studies. The advantage of primary data lies in its specificity to the research question, ensuring relevance and accuracy. Secondary data, while more readily available and cost-effective, may lack the precision of primary data. The combination of both sources can lead to a more comprehensive understanding of the life cycle impacts of supercapacitors[18].

A total of 17 articles of the reviewed literature sources incorporated primary data in their life cycle assessment process. They utilized and conducted major Life Cycle Inventories (LCIs) to directly measure and assess environmental impacts throughout the supercapacitor life cycle. As mentioned in the previous section, a substantial portion of the reviewed articles concentrated on investigating the environmental impacts of the electrode material. The primary data in these cases pertained to the production process of the electrode material. The research focusing on primary data related to the production of electrode material includes studies by Weil *et al*.[19], Sharma *et al*.[20], Li *et al*.[21], Glogic *et al*.[22], Wang *et al*.[23], Zhang *et al*.[24], and De *et al*.[8]. In these studies, the primary data were normalized based on the functional unit of production, ranging from grams of Co_3O_4 in Sharma et al.'s study to the production of 1000 kg of activated carbon as an electrode material in the research of Wang *et al*. [20,23].

According to Jiang *et al*. [14] and Glogic *et al*. [15], the electrode produced in a three-electrode system was investigated. The primary data for the construction of the electrode in the LCA were normalized based on the functional units of 1 and 5 Farad, respectively.

In the research conducted by Zimmerman *et al*.[10], Cossutta *et al*. [13], Chigada *et al*.[25], Li *et al*.[26], Dericiler *et al*.[27] and Hatzfeld *et al*.[11] preliminary data for a supercapacitor, including its electrodes (positive and negative), separator, electrolyte, current collector, and other components, were considered in the LCA. Full life cycle inventories were accessible for 15 of the studies that made use of primary data as a part of their methodology.

Finally, the software tools used for the LCA are an important aspect. Approximately 66% of the reviewed studies used SimaPro, OpenLCA, and GaBi as their LCA software. In addition, one article used Umberto [19], and another article utilized eBalance software [24]. In one of the articles, no details were provided about the specific software used [7].

3.1.3 Impact assessment methodology

The majority of the reviewed studies focus on greenhouse gas (GHG) emissions. Global Warming Potential (GWP) is the most frequently assessed category (17 studies), followed by Cumulative Energy Demand (CED; 5 studies). Other environmental impacts, such as urban land occupation (ULOP) or agricultural land occupation (ALOP), are considered less often. Fourteen studies quantify impacts in additional categories, mainly human toxicity (HTP), abiotic depletion (ADP), acidification (AP), eutrophication (EP), and ozone depletion (ODP) and marine ecotoxicity (METP). The impact assessment methodologies used for quantifying these impacts are ReCiPe (ten studies), CED (four studies), CML (three studies), IPCC 2013 (two studies), and 5 more study that use other method.

Almost all reviewed studies used midpoint indicators, and only the two studies that used ReCiPe (endpoint) and ECO-indicator for the impact assessment calculate an endpoint result. Figures 2.a and c show the impact assessment methodology and the categories assessed.

3.1.4 Environmental impact of supercapacitors

A discussion of the environmental impact of supercapacitors requires a comparison of results found in literature that could enable the estimation of average values for a set of given parameters. In this review, however, the comparison of results obtained in LCA studies poses several challenges. Firstly, a broad variety of functional / reference units have been used in different studies to represent the environmental impacts of the technologies. A few examples include capacitance (in F), storage capacity (in kWh), amount of material produced (in kg) and current flow (in mAh), among others, which hinders direct comparability. In some cases, there is neither enough data provided to convert functional units into a single unit that could allow comparison between studies. This discrepancy among functional units obeys to the variety of technologies and applications as well as to the different set of boundaries defined in each study. Some studies, for instance, focus on the synthesis of active material for the electrode and therefore are limited to the analysis of environmental impacts of mass of material produced *e.g.* kg of graphene[27], $Na_2Ti_3O_7$ [8] or activated carbon[23]. Other studies analyse larger systems with specific SC applications with examples such as electromobility in Germany (FU =1 vehicle lifetime of 12 years with a driven distance of

150000 km)[10], multifunctional facades (FU = kWh / m^2) [11] and use in city buses in Finland (FU = kWh)[12].

Additionally, the diversity of Life Cycle Impact Assessment (LCIA) methodologies employed in different studies results in the presentation of outcomes in varied units within specific impact categories, making direct comparisons also challenging (see Figure 2a). Some examples of employed methodologies include Cumulative Energy Demand (CED), Global Warming Potential (GWP) as defined by the International Panel on Climate Change IPCC, the ReCiPe methodology and the CML method among others. It must be noted that most studies provide a discussion of at least the GWP, with some also providing a list of total impacts in other categories.

As discussed in preceding sections, it is noteworthy that only seven studies have undertaken a comprehensive life cycle assessment encompassing the entire supercapacitor, including electrodes, electrolyte, and current collector. Among these studies, three employ a cradle-to-grave system boundary, while the remaining four adopt a cradle-to-gate system boundary. This variation in system boundaries further adds to the complexity of comparing the outcomes across different studies. Other examples of discrepancies between system boundaries hampering comparability relate to the manufacturing conditions of each technology. On the one hand, the use of different electricity mixes in the production phase may influence largely the total environmental impacts. Figure 2b illustrates the different regions used as source of electricity in the production of supercapacitors in this review and the number of studies for each one.

The total number of studies in the graph differs from the total studies screened due to some studies evaluating several regions. Based on the Figure 2c, grids from Germany, China, Europe (average), India and Sri Lanka among others have been used for the production stage of the supercapacitors, being China the most frequently found (a total of 6 studies). In five studies it was not possible to identify the electricity mix used or did not apply (*i.e.* the analysis was focused only on CED). Also related to the manufacturing conditions of the supercapacitors is the scale of production, which plays a vital role in the calculation of environmental impacts and must therefore be considered in the case of comparison. A total of 11 studies were found to describe SC production under lab-scale conditions whereas a total of 12 studies relate to industrial or prospective industrial SC production.

The previous conditions make it impossible to provide a meaningful global picture of the environmental impacts of supercapacitors at the current stage of analysis. To do so, a unification of the life cycle inventories, where provided, must be firstly conducted to homogenize system boundaries and to provide a common base for a subsequent recalculation of the environmental impacts. By doing so, a fair comparison of the unified models would be feasible.

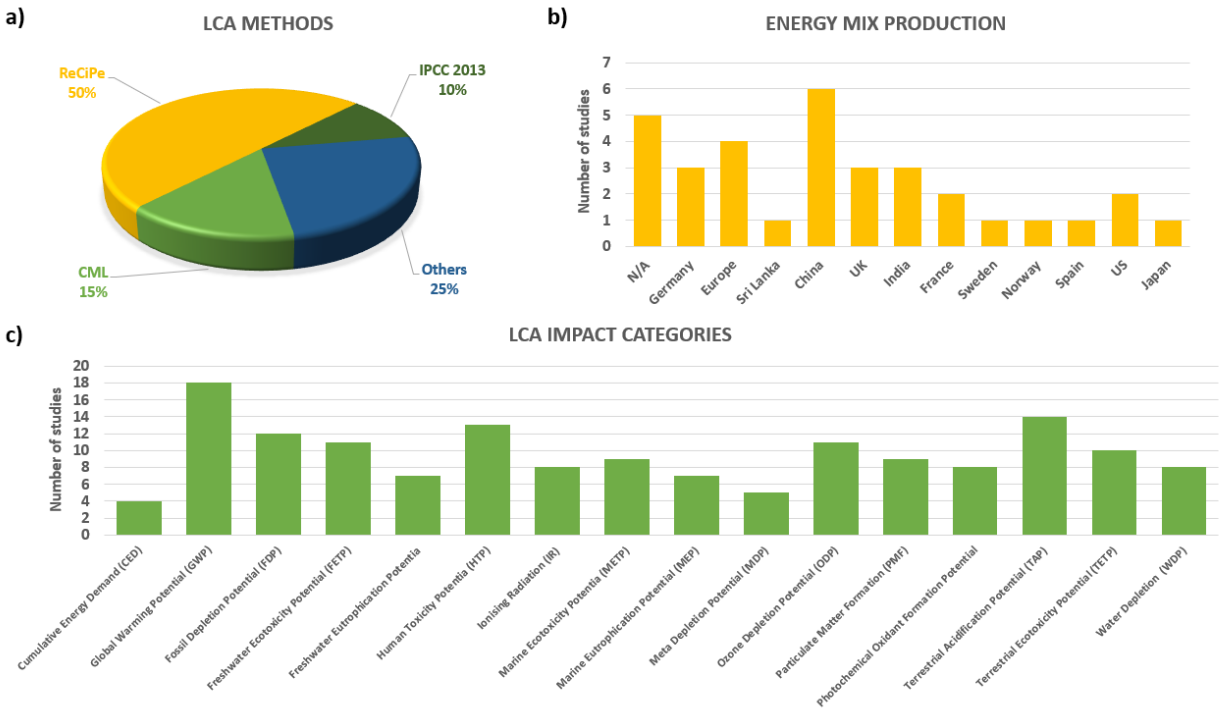

Figure 2. Life cycle assessment literature review a) LCA methods assessed, b) Number of studies per electricity mix (region) and c) Impact categories in the selected LCA studies.

3.1.5 Sensitivity analysis

An important component to ensure the robustness and reliability of LCA studies is the conduction of sensitivity analysis. This type of analysis is primarily intended to identify and quantify the influence of specific parameters on LCA outcomes and to understand how modifications to these parameters affect the overall conclusions of the study. Accordingly, a sensitivity analysis is normally conducted in order to assess the reliability and coherence of the findings. In the reviewed literature, only seven studies have conducted sensitivity analyses related to SCs.

In terms of the most relevant parameters for sensitivity analysis in the reviewed studies, the energy supply chain and supercapacitor materials and components can be highlighted. The studies that focus on the energy mix consumed in the production or use phase of the supercapacitor include Zimmerman *et al*.[10], Cossutta *et al*.[13], and Sharma *et al*. [20].

Cossutta *et al*.[13] demonstrated that future scenarios, as presented in their LCA study on graphene and activated carbon in a supercapacitor application, suggest a substantial reduction in greenhouse gas emissions associated with supercapacitor manufacturing and use. As a result of the change in electricity supply chain from the EU electricity mix to the Norwegian electricity mix, this reduction is possible.

The research conducted by Wang [23] focuses on the use of activated carbon in supercapacitors. This study delves into the LCA of activated carbon production from Lignocellulosic Biomass as electrode material. The findings in the sensitivity analysis sections underscore that the use of KOH (potassium hydroxide) without recycling not only results in a significant environmental impact in terms of greenhouse gas emissions but also poses risks to human toxicity. Notably, wastewater containing KOH in an aqueous mix is identified as a potential source of hazardous waste. Consequently, the recovery of KOH for reuse emerges as a viable strategy, offering both economic and environmental benefits to activated carbon production. Table 1 provides details about sensitivity analyses in other studies.

Table 1. Main characteristics of LCA studies (scientific article) on Sc, Cap and LFP identified by literature search (2010-2023)

YEAR	TECHNOLOGY	FUNCTIONAL UNIT	LCA MODELLING APPROACH	SOFWARE & DATA BASED	DEVELOPMENT STAGE	SENSITIVITY ANALYSIS	REF
2015	SC	1 vehicle lifetime of 12 y with a driven distance of 150000 km	Cradle to grave	Umberto 5.5, Ecoinvent 2.2	Industrial	Electricity supply chain	[10]
2018	Cap	1 kg for each electrodes with capacitance of 1 μF	Cradle to Grave	_	Prospective industrial	Primary energy consumption	[7]
2019	SC	1000 mAh at the current density of 1 A g^{-1} over the lifetime of the electrodes defined by the capacity fade of 20%	Cradle to Gate	OpenLCA 1.5, Ecoinvent 3.3	Lab scale	Process efficiency and electrochemical performance	[22]
2019	SC	1 ton of V_2O_5 Crystals	Cradle to Gate	GaBi 8.7, Ecoinvent 3.4	Lab scale	-	[21]
2019	SC	1 g Co_3O_4 (electrode material)	Gate to Gate	SimaPro 8.0.3.14, Ecoinvent v 3.1	Lab scale	Electricity supply chain	[20]
2019	SC	One supercapacitor rack of 5 supercapacitors with capacitance of 5 F	Cradle to Grave	GaBi 7.0	Industrial	Electricity supply chain	[13]
2021	SC	5 F	Cradle to Gate	SimaPro	Lab scale	-	[14]
2021	LIC	Cells which make a 48 V LIC module	Cradle to Gate	SimaPro, Ecoinvent 3.5	Lab scale	-	[25]

2021	SC	1 micro SC	Cradle to Gate	Simapro	Lab scale	-	[26]
2022	SC	1F	Cradle to Gate	Open LCA, Ecoinvent 3.6	Industrial	-	[15]
2022	SC	One batch of graphene production (electrode material)	Cradle to Grave	Simapro 9.1.1.1 , Ecoinvent 3.	Lab scale	-	[27]
2022	SC	1000Kg of AC (electrode material)	Cradle to Gate	Simapro 9	Industrial	Recycling of KOH and use of Steam activation	[23]
2022	SC	1 g of floc sludge for carbon electrode material	Cradle to Gate	eBalance, ecoinvent v3.1	Lab scale	-	[24]
2022	SC	kWh/ 1m^2 & 1 faced panel	Cradle to Gate	openLCA 1.10.3	Prospective industrial	Different functional units	[11]
2022	Cap	1,000,000 pieces of the AECs with 25 V rated working voltage and 150 μF rated capacitance	Cradle to Grave	Gabi 10.6.1.35	Industrial	Electricity supply chain and primary aluminium production	[28]
2022	Cap	100,000 high-voltage AECs (420V, 680 μF), each with 3000 operating hours	Cradle to Grave	Gabi 10.6.1.35	Prospective industrial	A 5% increase from baseline for electricity used in production, aluminum ingot mass for anode foil, aluminum ingot mass for cathode foil, design	[29]

						capacitance, and electrolyte mass.	
2023	LFP	KWh	Production+ use phase	OpenLCA 1.11,Ecoinvent 3.8	Industrial	A 10% increase from baseline for each parameter in the manufacturing and use stages	[12]
2023	SC	1 F supplied at 3.5 V 1 W supplied for 1 min 1 Wh supplied in 1 min	Cradle to Gate	OpenLCA 1.11.0, Ecoinvent 3.8	Prospective industrial	-	[30]
2023	SC	1 kg of PANI/GO nanocomposite (electrode material)	Cradle to Gate	OpenLCA	Lab scale	-	[31]
2023	SC	1 kg of NTO (electrode material)	Gate to Gate	SimaPro 9.0.0.29 , Ecoinvent 3.1	Lab scale	-	[8]

3.2 Life cycle costing

The search conducted on LCC reveals a significantly high variety of results. Currently, real-world use of supercapacitors is limited, yet they remain as a promising alternative for some applications where high power is required. Thus, many of these publications focus on the cost comparison of a particular system that predominantly uses fossil fuels (or merely does not integrate an energy recovery system) with the novelty of installing a supercapacitor storage system.

Most of these publications are based on mere simulations whose economic feasibility is not analysed. Moreover, if available economic information on this supercapacitor technology is already scarce, information of lithium-ion capacitor systems is still poor (or, in the case of sodium-ion capacitors, simply non-existent).

In order to make available information concerning supercapacitor LCCs, a comprehensive review of the relevant academic literature has been carried out including a varied selection of academic papers, global and market reports and other relevant publications, with a total of 41 sources. In particular, this comprehensive review goes beyond traditional research publications, as it incorporates insights derived from projects funded by the EU research and innovation framework programs as well as information from the technology manufacturers themselves. Among them, just 33 publications end up having useful information.

With regards to EU projects, a total of 7 projects were identified using the previously mentioned strings and via the CORDIS portal. These projects were focused on development cost-efficient materials. However, most of them did not provide information regarding cost analysis. One project (AUTOSUPERCAP) resulted in a publication already identified via the other academic portals. Other projects (POSEIDON and GREENCAP) have just started in 2023 and has not published yet information. Figure 3 illustrates the number of studies and EU projects concerning LCC per year of publication:

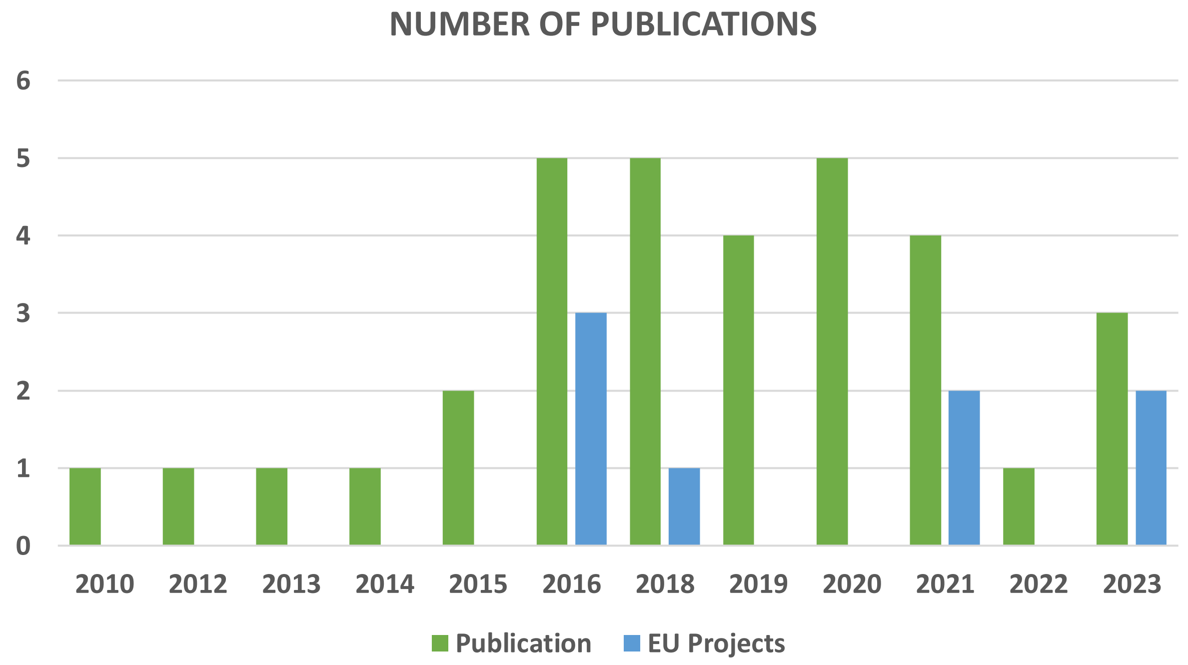

Figure 3. Number of LCC publications and EU projects per year between 2010 and 2023

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3.2.1 Goal and scope

After a screening of the identified literature, it could be observed that a majority of studies analysed hybrid energy systems, with the integration of supercapacitors and renewable energies (principally solar) as well as the hybridization of various energy storage systems, principally based on lithium-ion or lead-acid batteries.

Among the reviewed articles that consider a hybridization of supercapacitors and a renewable energy, in 2018, N. Luta *et al*. [32]analysed the deployment of a Hybrid Energy Storage Systema (HESS) combining hydrogen fuel cell and supercapacitors with photovoltaic panels. In addition, Conte *et al*.[33] analysed the hybrid lead acid battery-supercapacitor storage system for an electric forklift.

In terms of intended applications, in the Figure 4. Life cycle cost literature review the distribution of number of publications per application field can be analysed. As it can be observed, most of them do specify the application analysed. In addition, due to the growing interest in electromobility in recent years, a significant number of articles analyse the integration of supercapacitors in the transport sector. Indeed, Khaligh *et al*.[34] in 2010 reviewed the state-of-the-art Energy Storage Systems (ESS) for advanced hybrid vehicular applications and addressed as well ultracapacitors for future hybrid vehicles. Apart from electric vehicles, Wieczorek *et al*.[35] in 2019 carried out a cost comparison of different configurations of a hybrid energy storage system based on battery-only or supercapacitor-only storage in an electric city bus and Morandin *et al.* [36] reported the results of a study for moving from a diesel-based watercraft propulsion technology used in Venice to a supercapacitor-based electric propulsion system.

Some publications have also been found related to the integration with renewable energies. In particular, in 2021 Kumar *et al*.[37] carried out an economic comparison between a battery and supercapacitor for hourly dispatching wave energy converter and Ayodele *et al.* studied in 2018 the integration of supercapacitor in a battery/PV system for remote agricultural farm power application with the aim to increase battery lifetime and thus, to reduce life cycle cost.

In the stationary field, Yousef Pourjamal [39] has published in 2023 a comparative study of the techno-economic performance of various energy storage solutions (including supercapacitors) for fast-acting grid balancing applications. In addition, some companies such as Maxwell, Eaton and Riello have also published a cost analysis of their supercapacitor-based systems for Uninterruptible Power System (UPS) applications.[38, 39].

3.2.2 Data sources

As in the case of LCA, in LCC, the origin of the information is crucial to ensure the quality of the study. In general terms, data can be categorized in primary data and secondary data. The European Commission defines primary data as data from specific processes within the supply chain of the user of the product environmental footprint method. Primary data are site-specific, company-specific or supply chain specific. In contrast, secondary data refers to data that is not from a specific process, data that is not directly collected, measured or estimated but rather sourced from a third party LCI database. They usually include literature data [40].

Within the articles analysed, a large majority use secondary data. Specifically, in 2018, Luta *et al*.[32] used HomerPro software to investigate the model, simulate and optimise the configuration of the system, in addition to estimating the cost of installation and operation of the system during the entire operation time. Other software employed for the simulation is Matlab with Simulink tool. In this regard, Wang *et al*.[41] developed a new multi-strategy snake optimizer in MATLAB environment in order to look for the minimum LCC of the entire system (wind and photovoltaic power generation with battery and supercapacitors). In the case of Kumar *et al*.[37], the cost optimization of the ESS (a wave energy converter with supercapacitor bank) was conducted in the MATLAB/Simulink platform, considering both cycling and calendar aging.

However, there are some articles that employ primary databases. In fact, in the case of Mao *et al*.[42] an economic evaluation was carried out for energy storage options in an industrial microgrid with Maxwell BCAP3000 supercapacitor cell technical and economical specifications. In addition, in 2020, Saarentausta *et al*.[43] developed a technical and economical sizing of an electrical energy storage for a hybrid working machine gathering information for supercapacitor or lithium-ion capacitor module manufacturers such as LS Mtron, Skeleton, Sech, Maxwell, Musashi Technologies (previously, JM Energy), and AOWEI. In a similar way, Mongird *et al.* [44]conducted a technical and economical comparison of different energy storage technologies (including ultracapacitors) after conversation with vendors and stakeholders. As stated before, and regarding primary data, some companies such as Maxwell, Eaton and Riello have also published a cost analysis of their supercapacitor-based systems. [38, 39]

3.2.3 Impact assessment boundaries

When analysing costs, it is important to know the boundaries of the system under investigation. Thus, in the energy storage sector, and in particular using lithium and sodium ion supercapacitor or supercapacitor technology, the smallest unit to consider would be the different elements that make up a cell. In turn, the largest unit to be analysed would be the complete system of the specific application, which encompasses both the storage system and the use-phase.

In this sense, **Error! Reference source not found.**, illustrates the distribution of publications per boundaries considered. As it can be seen, few articles are based solely on the cost analysis of the different materials that make up a cell (in dark green), while more than a third analyse the entire system (in yellow). There are also significant publications that consider the functional unit in the battery pack (in light green), while there are fewer articles that analyse the cost of the cell (in blue).

Regarding the studies about electrode materials, just two publications analyse the cost of electrode material. In particular, they focus on the activated carbon employed in the processing of the electrode. In this sense, Weinstein *et al*.[45] stated the price of different carbon producers while Wang *et al.* [49] analysed the cost production of activated carbon, together with the LCA.

When extending the boundaries to the cell level, five articles were found to base the LCC analysis on the cell. Among them, Mao *et al*.[42] relied on the economics of a 3000F - 2.7V Maxwell supercapacitor to size the storage system and, consequently, to calculate the cost of installing and replacing the cells required for its installation. Similarly, Pourjamal *et al*.[46] from the economics of a 3200F - 2.85V supercapacitor, in this case from Skeleton company.

By extending the borders to a battery pack, the number of publications increases. For example, Gaetani-Liseo *et al*.[47]started from the investments costs of a supercapacitor battery pack investment cost and through simulation of the load profile of the system analysed, obtained the Levelised Cost of Energy (LCOE) of the system. In 2010, Khaligh *et al.*[34] reviewed the technical parameters of an ultracapacitor pack including the system cost. The paper analysed the state-of-the art of different storage options available at that time in electric vehicles. Apart from battery pack costs, the entire system of the vehicle was also analysed. In this sense, more than a third of the publications considered the entire system. In addition to the one mentioned just before, Gbadegesin *et al*.[48]compared the Levelized Cost of Hybrid Energy Storage System of different hybrid combinations on the basis of the cell unit costs and Mongird *et al*.[44] analysed both technical and economic aspects of a complete Battery Energy Storage System (BESS) of different technologies including ultracapacitor. This BESS comprised not only the battery system but also the power electronics and all the equipment involved on it.

3.2.4 Life cycle stages considered

Comparing results obtained in different LCC studies is not straightforward. Firstly, the boundaries of the system analysed are not always the same, with articles found to limit the study to the material costs of the electrodes of a cell or, in other cases, where the boundaries are extended to the complete system encompassing both the storage system and the use-phase. Secondly, the functional unit used for the analysis varies. In this respect, the results of the articles are shown per kW, kWh, kW-year, year, km, using costs in euros (€), dollars ($), pounds (£) and polish zlotys (PLN). This discrepancy between units is due to the different boundaries and applications analysed, as well as the stages considered in the study.

Regarding the different cost stages analysed, there are different terminologies used in the literature. On the one hand, Capital Expenditures (CAPEX) refers to the initial costs of a product, taking into account the various expenses associated with product implementation. On the other hand, Operational Expenditures (OPEX) encompasses the costs associated with the repair and inspection tasks. However, some articles do not cover costs under these two terms, but analyse other more specific aspects. Therefore, for this analysis, the terms use, operation & maintenance (O&M), replacement and disposal cost have been included, in order to faithfully analyse the results shown in the different sources of information. **Error! Reference source not found.** analyses the number of publications that analyse the different life cycle stages mentioned, distributed per boundaries.

With regards to the electrode material, Wang *et al*.[23] in 2022 considered not only the investment costs related to the production of activated carbon, but also detailed the costs associated with operation of the production plant.

Regarding the cell level, Saarentausta *et al*.[43]and EIT InnoEnergy in 2020 [49] just analysed the CAPEX cost of the cells. Pourjamal *et al.* [46] studied in 2023 not only CAPEX cost of the cell units but also the OPEX costs, considering a 10-year lifetime of the cells. Furthermore, in the case of Mao *et al.* the authors not only consider the CAPEX cost but also the O&M costs assuming a fixed number of replacements incurred during the lifetime of the system. In addition, it is worth mentioning that in the case of Wang *et al.*[41], the authors consider the investments costs, operating and maintenance costs and also the disposal costs (salvage cost and end-of-life).

When considering the battery pack, most of the articles analyse the CAPEX cost which is merely the investment cost of the storage system. In particular, Carter *et al.* [53] studied the investments cost of two battery packs of 30 supercapacitors consisting of 1700-2600F cells and Wieczorek *et al*.[35], studied a battery pack of 222 cells in series and 13 or 38 cells in parallel. Other articles are based in the use cost, in which, based on simulations, parameters such as the Depth of discharge (DoD) and the lifetime are considered [33], [50]. In terms of OPEX, replacement or O&M costs, three terms are differentiated in order to reproduce the information of the articles strictly. For example, Kim *et al.* [50]included under the OPEX costs the fixed O&M costs, and the cost of fuel and electricity. However, Gbadagesin *et al*.[48] analysed separately the O&M costs and the replacement costs. Finally, there are also a few articles that consider the disposal costs.

In terms of the entire system analysis, the majority of the literature focus on the CAPEX and investments costs [44, 48, 50]. As an example, in 2016, Tomczyk *et al*.[51] implemented a modelling of the cost-effectiveness of a railway line electrification. The study included the cost of buying the vehicle (a railway) but also maintenance costs. It is worth mentioning that among the different documents that analyse the entire system costs, none of them included the disposal on their studies.

3.2.5 Special remarks on LCC review

As seen in the previous section, one of the aspects to consider in the costs of an energy storage system is the cost associated with O&M as well as the cost of replacement. As with Li-ion batteries, performance and lifetime of storage systems based on supercapacitors or hybrid capacitors are affected by the conditions under which they operate. In this respect, both the operating temperature and the depth of discharge of each cycle are factors that affect the degradation of the battery, and thus its life expectancy. Therefore, the shorter the life expectancy, the greater the need for replacement of the unit, and consequently the higher the cost of O&M. In this regard, Song *et al*.[52] analysed the degradation cost of a hybrid energy storage system (HESS) in a year, by month by the study of different operating temperatures. In a similar way, Gbadegesin *et al.*[48] investigated the effect of system degradation on energy output and replacement costs over a 20-year period.

On the other hand, it is important to note that, when analysing a complete power system, the costs do not only consider the supercapacitor, but also many other electrical components that comprise the system. These other components vary depending on the application, being, in a stationary application, the power control system (PCS), Balance of plant (BOP) CS, BOP and Construction and Commissioning (C&C), among others. In this sense, Mongird *et al*.[53] reported a cost breakdown of the CAPEX.

Finally, it is important to note that, when talking about costs, the year of publication is crucial. In general, costs fluctuate depending on the demand for the systems, but also on other external factors such as the materials crisis or geo-political and social problems. Therefore, the described cost results cannot be compared due to differences in publication dates. Similarly, some publications make a cost prediction. In this respect, Mongird *et al*.[44], in 2019 projected the CAPEX and O&M costs of entire systems for year 2025. In a similar way, EIT InnoEnergy[49] published a cost evolution from year 2005 with forecast until 2030 for ultracapacitors.

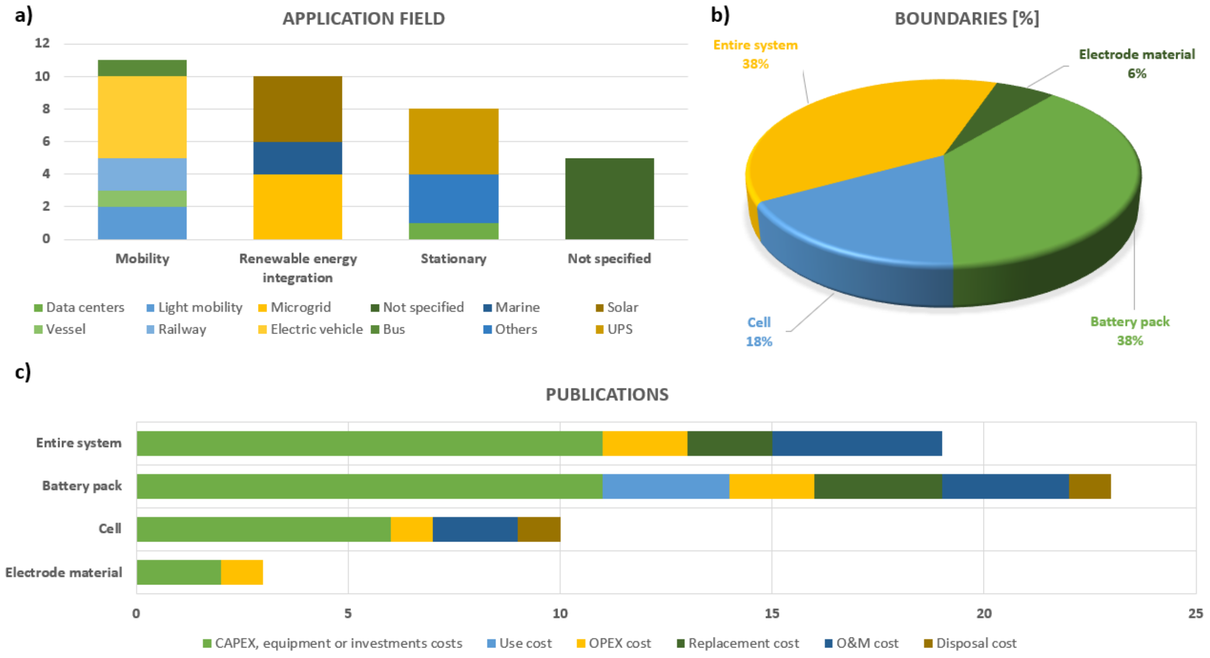

Figure 4. Life cycle cost literature review a) Number of studies by application field, b) Percentage of publications by boundaries, c) Number of publications per life cycle stages considered.

Table 2. Main characteristics of LCC studies on supercapacitors identified by literature search (2010-2023)

YEAR	TECHNOLOGY	FUNCTIONAL UNIT	DEVELOPMENT STAGE	APPLICATION	BOUNDARY	COST ANALYSIS	REF
2010	Batteries, UC and FC	$	State-of-the-art review	Mobility	Battery pack	Cost	[34]
2012	SC	£	Unit market prize	Mobility	Battery pack	-	[54]
2013	SC	$/kg	Component market prize	Not specified	Electrode material	-	[45]
2013	SC	€/kW	Early stage	Mobility	Cell	Cell production cost	[55]
2014	UC	$	Simulation	Mobility	Entire system	Cash flow in 12 years	[56]
2015	LIB, SC	$/kW, $/kWh	Model	Renewable energy integration	Cell	Capital, O&M and replacement costs	[57]
2015	Battery, UC, LIB, FC	€, kg per €	Simulation	Mobility	Entire system	CAPEX, running costs and payback times	[58]
2016	SC, batteries	Parameter/%	Simulation	Renewable energy integration	Battery pack	Current gain, energy losses and global efficiency per cost (%)	[59]
2016	Pb-acid, SC, LFP	$/month, savings (%)	Simulation	Stationary	Battery pack	TCO	[60]
2016	Battery, SC	$/kWh	Simulation	Stationary	Entire system	Annual revenue, cost, and profit	[61]
2016	SC	PLN/year	Existing and planned	Mobility	Entire system	Cost of investment, maintenance and scrapping costs	[51]
2016	SC, LTO	€/day	Existing and proposed solution	Mobility	Battery pack	Operating costs	[62]

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2018	SC, battery	$	Simulation	Renewable energy integration	Entire system	Initial cost, Replacement cost and O&M cost.	[63]
2018	FC, SC	$/kW	Simulation	Renewable energy integration	Battery pack	Capital, replacement, O&M, salvage	[32]
2018	Pb-acid, SC	$/kWh, %	Simulation	Renewable energy integration	Battery pack	LCOE, CAPEX, reinvestment, O&M	[47]
2018	Pb-acid, LIB	$		Stationary	Battery pack	Average total cost, amortization CAPEX, OPEX	[64]
2018	SC and batteries	$/km, $	Simulation	Mobility	Entire system	Battery price, capital cost, electricity cost, replacement cost	[52]
2019	SC, battery	$, $/kW-year	Simulation	Renewable energy integration	Entire system	CAPEX, Fixed O&M, fuel cost, electricity cost	[50]
2019	Pb-acid, FC, LIB, SC	$/kWh	Simulation	Renewable energy integration	Entire system	Total Equipment and Installation Costs, Total O&M costs, Total Replacement costs	[48]
2019	LFP, NMC, SC	$	Simulation	Mobility	Battery pack	Initial and operational costs	[35]
2019	LIB, RFB, Pb-acid, NaS, Na metal halide, Zinc hybrid, pumped storage, flywheels, CAES, UC	kW, kWh	Market	Not specified	Entire system	CAPEX, O&M	[44]
2020	LIB, RFB, Pb-acid, NaS, UC...	$/kW-year, $/kW, $/kWh	-	Stationary	Entire system	CAPEX (with cost breakdown), Fixed OPEX	[53]
2020	Battery, SC	€	Simulation	Mobility	Entire system	SC and powertrain modification cost (€), total battery cost and forklift EoL (€), total cost of storage system (€) and LCC reduction (%)	[65]

2020	LIB, SC, LIC	€/kW, €/kWh	Market	Mobility	Cell	CAPEX	[43]
2020	UC, LIB	$/kWh	Industry	Not specified	Cell	Cost	[49]
2020	SC	kW	TRL9	Stationary	Battery pack	Initial cost, maintenance and replacement cost, disposal cost	[38]
2021	LIB, SC	kWh	Simulation	Renewable energy integration	Battery pack	ESS cost	[37]
2021	LIB, Pb-acid, SC	$/kWh	Simulation	Renewable energy integration	Entire system	Base cost, converter base cost, inverter base cost	[66]
2021	SC, LIB, Flywheel	kW	TRL9	Stationary	Battery pack	Efficiency cost, maintenance cost and CAPEX	[39]
2021	Batteries, SC, Flywheels	200 kW		Stationary	Battery pack	Initial cost, annual cost, maintenance and replacement	[67]
2022	SC	USD	Industrial	Not specified	Electrode material	CAPEX, OPEX, NPV	[68]
2023	SC	kW, kWh	Market	Not specified	Entire system	CAPEX, O&M	[69]
2023	SC	Yuan	Simulation	Renewable energy integration	Cell	Purchase, operating, maintenance, and disposal (salvage cost and end-of-life) cost of the equipment	[41]
2023	LIB, SC	€, €/MW, €/year	Market	Stationary	Cell	CAPEX, OPEX	[46]

4 Discussion and conclusions

Through this report, an analysis of the available studies of LCA and LCC for supercapacitors has been done. A methodological review has been carried out, in different search engines and with the use of different keyword strings.

In terms of LCA review, the system boundaries considered, data sources, the impact assessment methodology employed, and the environmental impacts analysed have been extracted as the main information for the review. In the case of LCC analysis, the analysed data sources were carried out by analysing the applications, boundaries and life cycle stages.

After this systematic review, it has become clear from the screening of environmental and economic assessments that, due to the heterogeneous boundaries used in literature, an estimation of average values in terms of total environmental impacts or costs is unfeasible. The broad variety of applications, types of technologies and system levels, combined with the limited number of studies that provide a detailed analysis (often related to very novel systems), make it impossible to draw meaningful and sensible conclusions regarding global impacts of SCs at this stage. The results found in literature may be suitable for discussions about the specific systems in each study, but little can be said of a broader picture for SCs. Thus, it remains unclear how generic SCs technologies may perform from an environmental and economic point of view. Further research is therefore necessary to adequately understand the sustainability aspects of this type of technology.

It must be noted that most studies provide fully or at least partially disclosed life cycle inventories, granting them with a certain level of transparency and enabling reproducibility and traceability of the results. This fact would also allow eventual reconstruction, homogenization and comparison between different systems leading to a clearer picture of environmental and economic impacts of SCs.

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5 Recommendation

The challenges faced during the conduction of this review, which have hampered the comparison of studies and the extraction of a general picture in terms of environmental impacts and cost, may also serve as motivation for the conduction of a follow-up study focused on the unification of boundaries and subsequent recalculation of cost and impacts. To do so, the life cycle inventories provided in literature can be adapted to a generic set of parameters and boundaries (e.g. electricity mix and system components) as well as to a single functional unit that may serve as common base for comparison. A distinction between production scales and TRL levels will also be necessary before drawing any conclusion, as this has a direct influence on the results. It must be noted that currently there are very few studies analysing similar system levels (active materials, electrodes, full capacitors, etc) and therefore the suggested comparison of unified systems will face several limitations and will also be subject to a large degree of uncertainty.

6 Risk register

Risk No.	What is the risk	Probability of risk occurrence[1]	Effect of risk[2]	Solutions to overcome the risk
WP8.1	Available publication related to the study not considered in the review.	2	3	As the expected effect of the risk is low, no mitigation measures are needed.

Table 3. Risk Register

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

[2] Effect when risk occurs: 1 = high, 2 = medium, 3 = low

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4	CNRS	CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS	France
4.1	IMN	NANTES UNIVERSITE (Affiliated)	France
5	UPS	UNIVERSITE PAUL SABATIER TOULOUSE III	France
6	FSU	FRIEDRICH-SCHILLER-UNIVERSITAT JENA	Germany
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Table 4. Project Partners

9 Appendix A – Quality Assurance

The following questions should be answered by all reviewers (WP Leader, peer reviewer 1, peer reviewer 2 and the technical coordinator) as part of the Quality Assurance Procedure. Questions answered with NO should be motivated. The author will then make an updated version of the Deliverable. When all reviewers have answered all questions with YES, only then the Deliverable can be submitted to the EC.
NOTE: For public documents this Quality Assurance part will be removed before publication.

Question	**WP Leader**	**Peer reviewer 1**	**Peer reviewer 2**	**Technical Coordinator**
	Marcel Weil (KIT)	Pierre Louise Taberna (UPS)	María Arnaiz (CICE)	Jon Ajuria (CICE)
1. Do you accept this deliverable as it is?	Yes	Yes	Yes	Yes
2. Is the deliverable completely ready (or are any changes required)?	Yes	Yes	Yes	Yes
3. Does this deliverable correspond to the DoW?	Yes	Yes	Yes	Yes
4. Is the Deliverable in line with the MUSIC objectives?	Yes	Yes	Yes	Yes
a. WP Objectives?	Yes	Yes	Yes	Yes
b. Task Objectives?	Yes	Yes	Yes	Yes
5. Is the technical quality sufficient?	Yes	Yes	Yes	Yes

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