2.6. Life Cycle Assessment of a Graphene-Based Supercapacitor: Environmental Hotspots and End-of-Life Strategies for Sustainable Energy Storage

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ABSTRACT

Global energy crises are increasingly driven by geopolitical tensions, depletion of non-renewable resources, and environmental degradation, placing significant strain on the energy supply chain. In response, there is growing momentum toward energy independence through sustainable alternatives, particularly renewable energy sources, which are essential for achieving net-zero carbon emissions and reducing reliance on fossil fuels. However, the integration of renewables into the energy mix necessitates advanced energy storage technologies to manage variability and ensure supply stability.
Supercapacitors (SCs) have emerged as a promising energy storage solution due to their high power density and durability, with applications spanning electric vehicles, renewable integration, and low-power electronics. Despite their potential, the environmental impacts and end-of-life management of supercapacitors remain underexplored and unregulated. This study conducts a comprehensive Life Cycle Assessment (LCA) of a graphene-based cylindrical supercapacitor, evaluating its environmental footprint across manufacturing, distribution, and end-of-life stages.
The focus of the study was placed on the manufacturing and end-of-life phases. The analysis identifies graphene oxide production as the primary environmental hotspot during manufacturing. For end-of-life, recycling consistently offers greater environmental benefits compared to incineration, particularly through the recovery of aluminium, graphene oxide, and PTFE binder. Effective recycling processes, especially for active materials such as doped graphene, are critical to minimizing emissions and maximizing the environmental advantages of supercapacitor technology.
Overall, the findings underscore the importance of robust recycling strategies and targeted process improvements to enhance the sustainability of supercapacitors, supporting their role in the transition to a low-carbon energy system.

INTRODUCTION AND AIM

Modern society's escalating reliance on electricity, propelled by advances in electromobility, the proliferation of mobile devices, and the expansion of the Internet of Things (IoT), necessitates the development of efficient, sustainable energy storage solutions1. The depletion of fossil fuel reserves further underscores the urgency for clean energy sources and advanced storage technologies to balance global energy demand and align with the United Nations Sustainable Development Goals, particularly SDG 7: Affordable and Clean Energy. Energy storage systems such as supercapacitors (SCs), batteries, and fuel cells are thus critical for harnessing renewable energy, supporting remote area power supply, electric transit, hybrid vehicles, and a wide array of portable electronic devices.
Lithium-ion batteries (LIBs) have achieved significant market penetration; however, they are constrained by limitations in power density and safety. In contrast, recent advancements in supercapacitor technology, particularly the use of super-doped graphene electrodes, have yielded substantial improvements in energy density, thereby broadening their applicability, including in electric vehicles1. Graphene, characterized by exceptional electronic and mechanical properties, has emerged as a pivotal material in advanced electrode manufacturing. Nevertheless, the environmental impact and cost associated with large-scale graphene production necessitate the development of effective recycling technologies to ensure sustainability.
Supercapacitors have garnered significant attention due to their rapid, reversible operation, superior cycling life, minimal maintenance requirements, and enhanced safety profile. Despite these advantages, their energy density remains inferior to that of batteries1. Notably, recent graphene-based architectures have achieved energy densities up to 200 WhL^{-1} at power outputs of 2.6 kWL^{-1}, attributed to their ultra-light mass and high ion-hosting capabilities. While conventional capacitors typically store charge in the micro- to milli-Farad range, supercapacitors operate between 100 and 1000 Farads, offering power densities several orders of magnitude higher than batteries, albeit with lower specific energy1.
The superior performance of supercapacitors is further underscored by their high specific surface area—approximately 10000 times greater than traditional capacitors—and their ability to store up to 1000 times more power than batteries, though with 3–30 times less charge. The enhancement of specific energy in supercapacitors is primarily achieved through the optimization of electrode materials, with carbon materials, transition metal oxides/hydroxides, and conducting polymers being the most prevalent choices. These devices also offer high system stability, lightweight construction, low heat generation, and versatility, making them particularly attractive for next-generation electronic and automotive

applications. A comparison of performances of super-capacitors, batteries, and traditional capacitors is reported in Table 1.
The principal limitation of supercapacitors remains their energy density, driving ongoing research into novel electrode materials capable of delivering both high power and extended operational life.

Table 1 Comparative analysis of selected technologies for electrical energy storage.

Property	Super-Capacitor	Capacitor	Battery
Specific energy (Wh/kg)	1-10	<0.1	10-100
Specific power (W/kg)	500-10000	10000	<1000
Discharge time (s)	S to min	10^{-6} to 10^{-3}	0.3 – 3h
Charge time (s)	S to min	10^{-6} to 10^{-3}	1 – 5h
Coulombic efficiency (%)	85 – 98	About 100	70 – 85
Lifecycle (cycles)	>500000	Almost infinite	~1000

Recent studies have demonstrated that nitrogen-doped graphene with diamond-like bonds can attain unprecedented energy densities while maintaining high power output in symmetric supercapacitors, highlighting the transformative potential of such materials1. The current supercapacitor market is dominated by activated carbon devices, especially within the automotive sector. However, the integration of doped graphene as an active material promises to enhance competitiveness and performance in portable energy storage applications1. Furthermore, advances in material efficiency and decarbonization of electricity generation could render graphene-based supercapacitors the least environmentally impactful option, with significant reductions in greenhouse gas emissions, material depletion, and photochemical ozone formation.
To comprehensively evaluate the environmental performance of these innovative devices, the Life Cycle Assessment (LCA) methodology, in accordance with ISO 14040, ISO 14044, and EN 50693 standards, is employed to assess impacts from raw material extraction through end-of-life disposal, adopting a cradle-to-grave approach. The European Innovation Council's TRANS2DCHEM Project exemplifies efforts to validate supercapacitor technologies in industrially relevant environments, addressing the growing demand for stable, high-performance, and safe energy storage in sectors such as data centres, IoT, grid storage, space, and medical devices.
This study specifically aims to assess the environmental impacts associated with the production and disposal of a Nitrogen and Fluorine Doped Graphene-based Cylindrical Supercapacitor manufactured by Itelcond s.r.l., focusing on critical factors such as precursor materials, energy consumption, and end-of-life scenarios. The findings are expected to inform the development of more sustainable and high-performing energy storage technologies.
References [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21]

METHODOLOGY

The *Life Cycle Assessment (LCA)* is an effective tool to identify best strategies of circular economy, those more promising to gain the highest environmental positive outcome of consumption and production in society. The validity of the methodology is assured by the *International Standards Organisation* (*ISO)* with relative norms, as the *ISO 14040: Principles and Framework* and *ISO 14044: Requirements and Guideline* along with recommendations from the European Commission (EC, 2013, 2021; EPLCA, 2003).
This section presents the adopted methodology in compliance with ISO 14040 and ISO 14044, in order to carry out a Life Cycle Assessment on a Cylindrical Graphene-based Supercapacitor.

Goal and scope definition

The goal of the present LCA study is to disclose the environmental performance of a new cylindrical graphene-based supercapacitor produced by Itelcond s.r.l.. The results will be helpful for the research on this promising technology and as internal data for the company. This study will take into consideration manufacturing, distribution, use, and end-of-life of the product, including maintenance and disposal of the supercapacitor. The declared unit chosen for this study is 1 Supercapacitor. Table 2 summarises the main characteristics of the device considered.

Table 2 Performance data of a single supercapacitor.

Parameter	Value
Capacitance (F)	4700
Voltage (V)	2.8
Stored energy (Wh)	5.12
Gravimetric Energy Density (Wh/kg)	35.05

System boundary
This study will cover the entire life cycle of the device, including relevant upstream processes as acquisition of raw materials, preparation procedures etc., and main manufacturing and processing steps; as well as a modelling of the use phase and different End-of-Life scenarios, namely a Waste-to-Energy (WtE) and a recycling scenario.
he analysed product system is reported more in depth in Fig. 1 System boundary considered.Fig. 1.
The study will be a *cradle-to-grave* assessment of the product. Primary data are available up to the gate of the producing company.

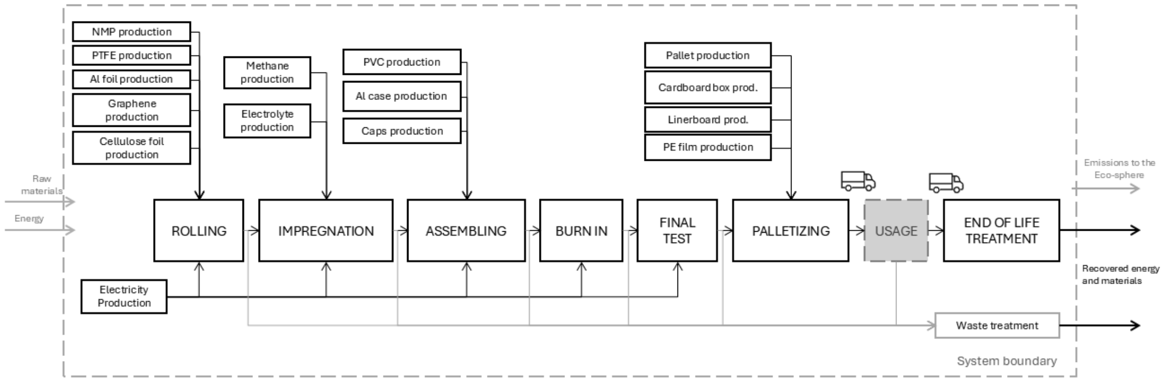

Fig. 1 System boundary considered.

Strong similarities in the manufacturing procedure have been found with previous studies conducted on aluminium electrolytic capacitors, in particular with the *snap-in* typology. The main manufacturing stages to be analysed are rolling, impregnation, assembling, burn-in, final test and palletizing. The assessed product is formed by a spiral of aluminium foil, coated with a graphene layer, where a paper separator is wound around themselves in the rolling phase: this unit is constituted by compressors connected to two winding machines. During impregnation, the paper foil in the dry capacitor - formed in the rolling phase – is soaked in a liquid electrolyte, thus forming a wet supercapacitor; at this stage, an autoclave system is adopted. Afterwards, the wet supercapacitor is assembled in an aluminium case, then to be insulated with a phenolic cap and an external PVC sleeve. Finally, assembled supercapacitors are tested in two different phases, namely burn-in and final test, where failed items are removed from the production line. In order to enter the market and reach final users, tested supercapacitors are packed and put on pallets, in the palletising stage.

Data quality and software
Data are provided by Itelcond s.r.l, a company located in Settimo Milanese (MI), Italy. Manufacturing details and energy consumption data are referred to year 2021 (along with some corrections), thus constituting primary data disclosed by the producing company. On the other hand, background data (i.e., chemicals, plastic materials, foils etc.) are provided by *ecoinvent 3.10* database.When geographical specifications are needed for data (e.g., electricity production), the Italian country is considered and, when more details are necessary, the Lombardy region is assumed (e.g., logistic data).
The professional software used to conduct the present LCA study is SimaPro® 10.1.0.5.

References [20], [21], [22], [23], [24], [25]

LIFE CYCLE INVENTORY (LCI)

Manufacturing phase
This stage involves data collection and calculation procedures to quantify relevant inputs and outputs of the chosen product system. The following paragraphs report data for each unit process within the adopted system boundary. Moreover, the production is modelled according to past records from Itelcond s.r.l. about snap-in typologies.
Since energy consumption is present in almost every unit process, it is here specified that two contributions are considered: one derived from the Italian electric grid and the other from the photovoltaic system built on the rooftop of the company; each unit process registers different contributions from the two sources. Thus, energy consumptions unit of mass (kWh/g) have been computed from past studies (year 2021) considering that, at present, the PV energy contribution is doubled since then, as declared by the manufacturer.
Packaging information will be introduced only at the palletising stage (see Fig. 1), because of lack of data for upstream packaging flows; this is mainly due to the early stage of the product development, which leads to uncertainty about potential material suppliers. For the same reason, components and materials transportation data are also not considered.
The production of dry capacitors begins with the rolling or winding of two electrodes and two separators, forming the core element, which is then impregnated with the ionic liquid electrolyte using heat and vacuum in an autoclave. The assembled wet capacitor is encapsulated in an aluminium case, sealed with a phenolic plastic cap, and insulated with a

PVC sleeve, with all components sourced from third-party suppliers and modelled using standard industrial processes. After assembly, the capacitors undergo a burn-in phase at elevated voltage and temperature to ensure reliability, followed by final testing with AC and DC currents to verify performance, with only passing units proceeding further. The completed supercapacitors are then packed into cardboard boxes with protective materials, strapped with polypropylene, palletized on wooden pallets, and wrapped in polyethylene for shipment, with all packaging and logistics modelled according to typical industry practices.

Distribution and Use Phase

In this section, the supercapacitor life span is described since the product leaves the gate of the manufacturing company up to the end of its usage, passing through the distribution stage. Related assumptions are reported below.

It is assumed that palletised supercapacitors are delivered to a distribution centre located in the Lombardy region, reached across the regional road logistic network. In particular, according to the most recent data provided by ISTAT (Istituto Nazionale di Statistica), 48.8 km are run - in average – in the Lombardy region, by road. The value refers to 2021 [26]. Due to the prototype-level of the supercapacitor, the final system where the item will be placed in (and used) is unknown, hence further transportation from distribution centres and additional activities are not part of the present description.

With regard to the *Use Phase*, it was excluded from the system boundaries due to the lack of a defined application scenario, which made appropriate modelling unfeasible. Nevertheless, this exclusion aligns with the objective of the study, which is focused on analysing the environmental impacts associated with the production and end-of-life disposal of the physical product manufactured by the company.

End-of-Life phase: from collection to treatment

According to Falbo et al., the end-of-life management of supercapacitors in Lombardy follows the WEEE (RAEE) system, involving collection by the “Centro di Coordinamento RAEE”, transport (averaging 78.7 km by lorry) to treatment plants, and subsequent recycling processes. The European Union prioritizes recycling over incineration for batteries and capacitors, with thermal and mechanical treatments—such as shredding and mild thermal processing—being common to recover about 90% of electrode active materials and 40% of the electrolyte, while non-recyclable fractions are incinerated. The recovered graphene, bonded PTFE, and electrolyte are considered valuable secondary materials, capable of substituting virgin counterparts, and the environmental benefits of this substitution are credited in the life cycle assessment (LCA) through system expansion. Downcycling effects are accounted for using literature-based substitution factors, and all energy used in recycling is fully allocated to the product. Packaging waste is modelled using recent Italian data, and all manufactured supercapacitors are assumed to enter the recycling process. The system is credited for producing secondary materials such as PTFE-bonded graphene, assumed to substitute virgin PTFE on a 1:1 basis, particularly for use as reinforcing fillers in epoxy resins, with substitution ratios based on physical properties and literature recommendations.

It is worth reminding that – since involving a credit for emissions that have not happened - *substitution method* is unique in creating negative results in an LCA [27].

References [9], [16], [23], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42]

LIFE CYCLE IMPACT ASSESSMENT

Sixteen impact categories have been considered, namely *Climate change; Ozone depletion; Ionising radiation; Photochemical ozone formation; Particulate matter; Human toxicity, non-cancer; Human toxicity, cancer; Acidification; Eutrophication, freshwater; Eutrophication, marine; Eutrophication, terrestrial; Ecotoxicity, freshwater; Land use; Water use; Resource use, fossils; Resource use, minerals and metals*.

In order to meet recommended impact categories by EN 50693:2019 and to run a fair comparison with past studies, the European *Environmental Footprint 3.1 V1.02 (adapted)* has been chosen.

Life Cycle Impact Assessment Results

The results obtained are relative to the already mentioned production phases considered in this Cradle-to-Grave analysis. These results aim at finding and highlighting the environmental hotspots in the production of this innovative supercapacitor. The relative contributions for each phase are reported in Fig. 2. As it can be noticed, major impacts are mainly related to *Dry Capacitor* (*Rolling* phase) production. The *Impregnation* phase in the only other notable contributor in the *Resource use, minerals and metals* category, making up to 24.7% of total positive impacts. *Rolling* phase makes for 94.46% of the Climate Change category positive impacts, and scores above 90% in all the other categories, with the exception of the *Resource use, minerals and metals* category.

Analysing more in depth the manufacturing chain, it has been found that the main contribution to almost all impact categories is due to Graphene Oxide production. Thus, in Fig. 3, relative impacts for 1 kg of Graphene Oxide synthesis are reported. From this analysis emerges the heavy influence of the electricity mix used on the environmental performance of the SC. Electricity production is in fact the main contributor to Climate change for the production of GO (55.21%), and for most of the other categories considered in the study, causing above 40% of the emissions in 9 different categories.

In this case study the energy mix considered also took into consideration the electricity generated by the photovoltaic system in the production site, meaning that the potential contribution of the electricity mix exploited could have even higher impacts on the production phase. Other notable contributors to the emissions of GO production are the production of sulfuric acid and potassium permanganate, two key components of the doping process.

Finally, the *Impregnation* process can be considered the second most impactful step of the production, with the production of the electrolyte being the biggest contributor to its emissions. Complete results can be consulted at Table 3.

The End-of-Life phase is responsible for the totality of negative impacts, potentially reducing the impacts of the Supercapacitor of around 20% in all categories, with a peak of 89% in the *Ozone depletion* category. A further analysis of the sole EoL impacts is reported in Fig. 4. The recycling of the Graphene Oxide brings the highest environmental benefits in all the analysed categories, with the exception of the *Ozone Depletion*, dominated by the impacts saved from recycling PTFE. The recycling of PTFE is also beneficial for the *Climate Change* category, making up for the 43% of the emissions saved from the whole EoL phase, closely following the recycling of Graphene Oxide (-47%). The recycling of the electrolyte and aluminium are also found to be notable.

Table 3 Total results divided in main life cycle stages.

Impact Category	Unit	Total	Manufacturing	Distribution	End-of-Life
Acidification	mol H+ eq	6.35E-02	7.81E-02	5.46E-06	-1.46E-02
Climate change	kg CO2 eq	5.25E+00	7.22E+00	1.37E-03	-1.97E+00
Ecotoxicity, freshwater	CTUe	4.01E+01	5.01E+01	5.20E-03	-9.98E+00
Particulate matter	disease inc.	4.57E-07	5.57E-07	1.11E-10	-1.00E-07
Eutrophication, marine	kg N eq	6.44E-03	7.37E-03	2.05E-06	-9.36E-04
Eutrophication, freshwater	kg P eq	1.63E-03	1.94E-03	9.20E-08	-3.11E-04
Eutrophication, terrestrial	mol N eq	4.98E-02	5.89E-02	2.24E-05	-9.22E-03
Human toxicity, cancer	CTUh	2.75E-08	3.50E-08	9.64E-12	-7.53E-09
Human toxicity, non-cancer	CTUh	5.45E-08	6.57E-08	1.21E-11	-1.12E-08
Ionising radiation	kBq U-235 eq	6.57E-01	7.95E-01	2.48E-05	-1.38E-01
Land use	Pt	1.97E+01	2.40E+01	1.15E-02	-4.32E+00
Ozone depletion	kg CFC11 eq	2.92E-06	2.59E-05	2.74E-11	-2.29E-05
Photochemical ozone formation	kg NMVOC eq	1.82E-02	2.24E-02	8.30E-06	-4.13E-03
Resource use, fossils	MJ	7.64E+01	9.36E+01	1.94E-02	-1.73E+01
Resource use, minerals and metals	kg Sb eq	6.43E-05	8.06E-05	4.41E-09	-1.63E-05
Water use	m3 depriv.	5.20E+00	6.83E+00	7.94E-05	-1.64E+00

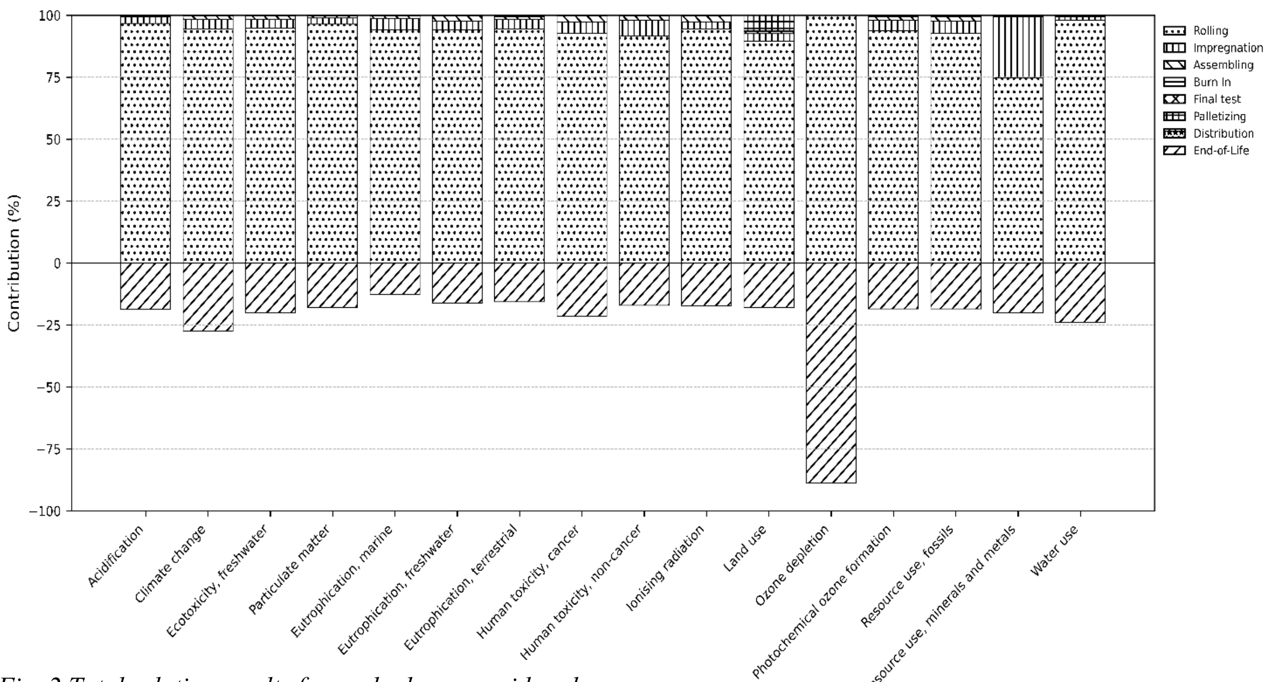

Fig. 2 Total relative results for each phase considered.

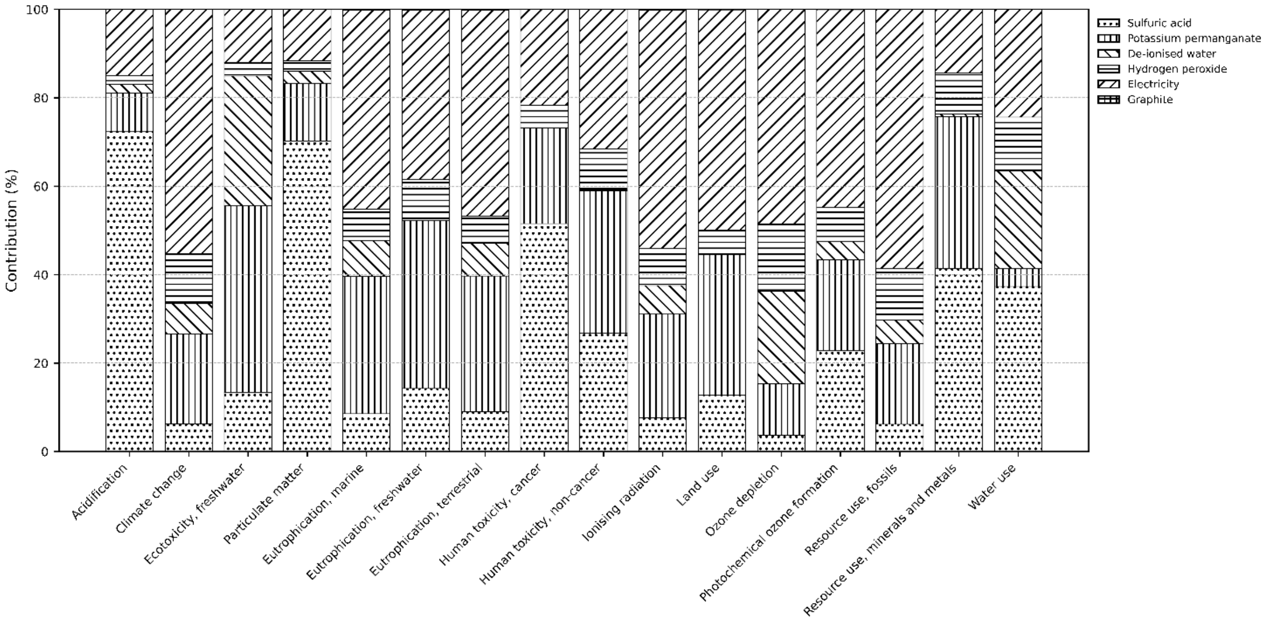

Fig. 3 Relative impacts for the production of 1kg of Graphene Oxide.

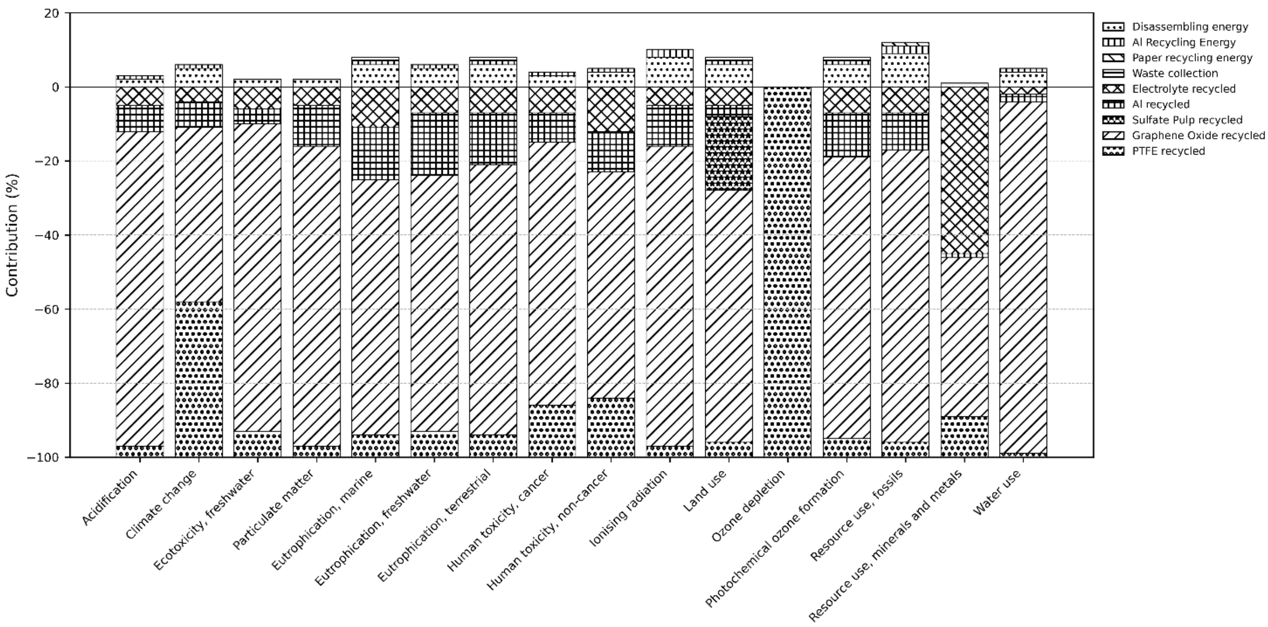

Fig. 4 Relative contributions to the End-of-Life phase for the disposal of 1 supercapacitor.

End-of-Life treatment scenario analysis

In this case, two different scenarios are analysed. For the baseline case, it is assumed that a SC reaching its end-of-life is recycled in compliance with the present Italian legislation. On the other hand, a comparative case sees used items treated in a Waste-to-Energy Plant (WtE). In particular, the model proposed by the database for *used capacitors incineration* includes the energy recovery section of a potential WtE plant but stating that all the burden is allocated to the waste disposal function. Hence, based on what has been previously reported concerning the *crediting* approach, avoided electricity and heat productions are taken into account, assuming an energy production (heat and electricity) of 18.38 MJ/kg SC in a co-generation plant.

In Fig. 5, results for the baseline case are reported in relative terms compared to those coming from the incineration scenario. In each impact category, the recycling scenario is always beneficial compared to the WtE case. On average, the recycling scenario offers potential impacts that are between 14% and 32% lower compared to those coming from incineration: impact categories benefitting the most are *Ozone Depletion* (-89%), *Climate Change* (-31%), *Ecotoxicity, freshwater* (-32%), *Human toxicity, cancer* and *Resource Use, minerals and metals* (-24%), while minor differences are registered for *Particulate Matter, Marine Eutrophication*, and *Land Use* (15%-20% reductions).

A comparison between the total results of the two scenarios can be seen in Table 4.

Table 4 Comparison of total impacts fot the two different EoL scenarios

Impact Category	Unit	Recycling Scenario	WtE Scenario
Acidification	mol H+ eq	6.35E-02	7.88E-02
Climate change	kg CO2 eq	5.25E+00	7.62E+00
Ecotoxicity, freshwater	CTUe	4.01E+01	5.93E+01
Particulate matter	disease inc.	4.57E-07	5.64E-07
Eutrophication, marine	kg N eq	6.44E-03	7.51E-03
Eutrophication, freshwater	kg P eq	1.63E-03	2.00E-03
Eutrophication, terrestrial	mol N eq	4.98E-02	6.04E-02
Human toxicity, cancer	CTUh	2.75E-08	3.61E-08
Human toxicity, non-cancer	CTUh	5.45E-08	6.91E-08
Ionising radiation	kBq U-235 eq	6.57E-01	7.98E-01
Land use	Pt	1.97E+01	2.35E+01
Ozone depletion	kg CFC11 eq	2.92E-06	2.59E-05
Photochemical ozone formation	kg NMVOC eq	1.82E-02	2.31E-02
Resource use, fossils	MJ	7.64E+01	9.71E+01
Resource use, minerals and metals	kg Sb eq	6.43E-05	8.11E-05
Water use	m3 depriv.	5.20E+00	6.86E+00

References [23], [24]

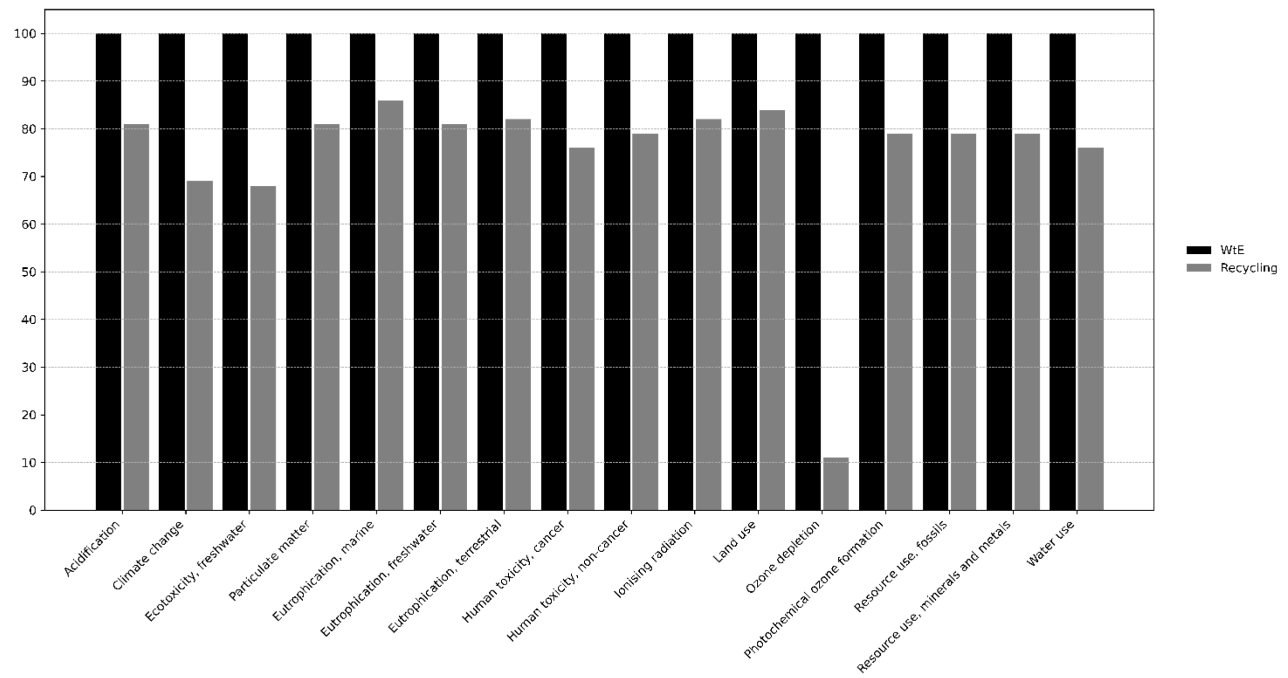

Fig. 5 Comparison of total impacts for the two diffferent EoL scenarios.

SUMMARY AND CONCLUSIONS

The aim of this work was to identify potential hotspots in the production of a novel Graphene-based Supercapacitor, identifying the most impactful components and processes, as well as assessing the benefits that a proper disposal scenario could bring to the sustainability of this technology.

This was achieved conducting a Cradle-to-Grave Life Cycle Assessment of the device. The study has taken into account the manufacturing and distribution phase, as well as the end-of-life of the device. For the EoL two possible scenarios were modelled: a recycling scenario chosen as base case and a waste to energy scenario.

The SC's main production stages have been analysed, registering consistent differences in relative terms. As reported in Fig. 2, major contributions are linked to the *Rolling* and *Impregnation* phases, which are to be considered as the two main hotspots. The manufacturing of one Supercapacitor with the technical characteristics considered impacts for 7.22 kg

CO_2eq on the Climate Change category, which is lowered to 5.25 kg CO_2eq thanks to the credits received from the EoL stage (-1.97 kg CO_2eq).

The manufacturing stage lays an average relative impact of about 86% for all categories in the *Rolling* phase producing the dry supercapacitor, most relevantly in Ozone Depletion (99.9%), Acidification (96.6%) and Water Use (97.5%). The production of doped graphene has been identified as the major source of impacts for the *Rolling* phase, and moving backwards in the production pathway the most relevant cause of potential impacts has been found to be the Graphene Oxide synthesis. In particular, it is underlined the contribution of energy consumption and potassium permanganate as oxidizing agent. For instance, electricity production scores 48% in Ozone Depletion, 55% in Climate Change and 59% in Resource Use (fossils) categories, while Potassium Permanganate records 34% for Resource use, minerals and metals, and 42% in Ecotoxicity (freshwater). Considering this, it has been seen that in the most impacting stage of manufacturing (i.e., rolling), contributions are usually not connected to the producer's direct operations (namely, energy for winding machines and solvent extractor) - recording average relative impacts per each category not higher than 1% - but rather in precursor materials and components (i.e., PTFE, doped graphene, Al-sheet).

Focusing on the End-of-Life stage, the energy used for disassembling the device was identified as the major contributor to the impacts of this phase, generating on average 73% of the positive impacts for each category and 75% of the Climate Change positive impacts specifically, followed by the energy for aluminium recycling (16% of all positive impacts on average). These environmental emissions, on the other hand, are greatly compensated by the avoided impacts credited due to the recycling of materials. Taking the Climate Change category as an example, the total positive impacts of the EoL phase are equal to 0.14 kg CO_2eq, compared to 2.18 kg CO_2eq credited for the recycling processes. The highest benefits are given by the recycling of the Graphene Oxide, scoring on average 67% of all avoided emissions, peaking at 95% of the total savings of the Water Depletion category. Other major savings to the environmental impacts are due to the recycling of PTFE, the electrolyte, and aluminium.

The comparison with a waste to energy scenario also highlights interesting aspects on the proper way of disposing of this type of devices, highlighting the importance of recycling to make this technology more sustainable. In this scenario, in fact, negative impacts are not present, increasing the total emissions in all categories. Considering a WtE scenario for the EoL, the total environmental impacts of the considered product rise to 7.62 kg CO_2eq for the Climate Change category. The EoL stage impacts now for 0.4 kg CO_2eq, instead of subtracting from the manufacturing emissions. Major advantages of recycling are found in the *Ozone Depletion* category, where recycling of PTFE saves up to 89% of total emissions, while for the other categories considered a cut of about 20% of the emissions was found. In particular the Climate Change potential is lowered by 31% (from 7.62 kg CO_2eq of the WtE scenario to 5.25 kg CO_2eq in the Recycling scenario).
In conclusion, the Graphene-based Supercapacitor is an innovative device regarded by manufactures, researchers, and European institutions to be able to reshape the energy storage field; however, before its adoption on a larger scale, particular attention has to be given to the sources of the electric energy used for manufacturing, as well as to proper disposal rules and pathways. A cleaner energy mix could in fact alleviate the impacts of producing this novel active material, while recycling of the components would improve the circularity of the whole device, since most of the relevant environmental burdens are linked to precursor materials.

This study has aimed at being a first attempt in evaluating potential environmental performances of Graphene-based Supercapacitors, while contributing to future research, innovative activities, design decision-making and to a true sustainable journey of the energy sector. Further steps in the research should include a proper real-life application and use phase modelling, as well as possible comparisons with devices with similar functions and characteristics.

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