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Graphene, MXene and ionic liquid-based sustainable supercapacitor

GREEN CAP

GREENCAP - Deliverable report

D5.2 Ex-post Environmental and Socio-economic Impact Assessment

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Summary

This report presents the ex-post environmental and socio-economic impact assessment and constitutes Deliverable D5.2 within Work Package 5 (WP5): Benchmarking & Impact Assessment of the GREENCAP project. As the first formal output of WP5, the document provides a comprehensive overview of the evaluation activities conducted under Task 5.2 (Environmental Impact Assessment) and Task 5.3 (Socio-economic Impact Assessment) throughout the past 36 months of project implementation.

The report consolidates the methodologies applied, the data collected, and the results obtained during this period, with the aim of assessing both the environmental footprint and the socio-economic implications of project activities. By integrating these dimensions, the assessment not only measures the effectiveness of GREENCAP in achieving its intended objectives but also provides valuable insights for benchmarking against comparable initiatives.

Furthermore, this deliverable serves as an essential reference for stakeholders, offering evidence-based findings to support decision-making, enhance transparency, and guide future activities within the project. In doing so, it lays the groundwork for subsequent analyses and recommendations, thereby contributing to the overall impact assessment framework of GREENCAP.

In alignment with the Horizon Europe Data Management Plan template, this deliverable is structured into four principal sections, each addressing a key dimension of the ex-post impact assessment.

The first section provides the overall context and conceptual framework for the assessment. It outlines the objectives, scope, and methodological underpinnings of the study, thereby situating the environmental and socio-economic evaluations within the broader aims of the GREENCAP project and the Horizon Europe program.

The second section focuses on the environmental dimension, with particular emphasis on the impacts associated with GREENCAP supercapacitors. This part centralizes on a cradle-to-gate life cycle analysis (LCA), assessing the environmental repercussions of the materials, processes, and technologies employed. The section also discusses the methodological considerations, boundaries, and assumptions that inform the LCA, ensuring transparency and robustness of the findings.

The third section addresses the socio-economic ramifications of the project’s technological advancements. It examines, in detail, the implications of critical raw materials (CRMs) in the development of supercapacitors, while also highlighting the project’s contribution to CRM-free methodologies. This dual perspective not only assesses potential risks and dependencies but also underscores opportunities for more sustainable and resilient value chains, industrial innovation, and long-term societal benefits.

The final section synthesizes the results of the preceding analyses, offering conclusions and critical reflections. It provides a discussion of the broader relevance of the findings, both for GREENCAP's future trajectory and for the wider scientific and industrial communities. In addition, this section identifies key lessons learned and outlines potential directions for further research and policy development.

The data underpinning this ex-post assessment were derived from a combination of sources, including:

- *Three structured questionnaires, each designed with a specific focus, aimed at collecting insights from both professional stakeholders and the general public regarding their perceptions, expectations, and prospects of supercapacitor technologies.*

- *Informal yet targeted expert consultations with members across different consortium institutions, aimed at capturing diverse perspectives on future trajectories for reducing dependency on, and ultimately eliminating, the use of critical raw materials.*

- *Technical knowledge and perspectives collected from project meetings, which provided the basis for systematic documentary research to capture the most recent advancements in both theoretical frameworks and applied practices related to the integration and substitution of critical raw materials within supercapacitor technology.*

Results clearly demonstrate that a substantial proportion of GREENCAP's raw materials are sourced within Europe, significantly enhancing resource autonomy and mitigating supply chain risks. The project achieved notable breakthroughs in CRM-free supercapacitor technologies, including:

- *Successful synthesis of graphene- and MXene-based electrodes from CRM-free precursors using environmentally sustainable and non-toxic processes.*

- *Development of next-generation electrolytes with superior thermal and chemical stability and inherent non-flammability, enabled by innovative ionic liquid synthesis.*

Together, these advances validate GREENCAP's leadership in pioneering sustainable, high-performance alternatives to CRMs, fully aligned with the EU's strategic priorities on green transition, circular economy, and technological sovereignty.

Ultimately, this ex-post assessment embodies GREENCAP's "develop by doing" philosophy—functioning as both a proof of concept and a continuous improvement mechanism for the project's impact framework. By combining hands-on experimentation with methodological refinement, GREENCAP delivers a lasting contribution to Europe's sustainability and innovation landscape.

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Abbreviations & Definitions

Abbreviation	Explanation
SCs	Supercapacitors
EU	European Union
CRMs	Critical Raw Materials
2DMs	Two-dimensional materials
ILs	Ionic liquids
LiBs	Li-ion batteries
DNM	Data Need Matrix
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
GWP	Global Warming Potential
ODP	Ozone Depletion Potential
CTUh	Comparative Toxic Unit for humans
AE	Accumulated Exceedance
CTUe	Comparative Toxic Unit for ecosystems
SMSs	SC management systems
EDLCs	Double layer capacitors
OKR	Objectives and Key Results

1 Introduction

1.1 Background of the ex-post impact assessment

The GREENCAP project has successfully advanced the development of supercapacitors (SCs) as high-performance electrochemical energy storage systems, contributing to the European Union's (EU) transition towards climate neutrality in line with its international commitments under the Paris Agreement, while also supporting the objectives of the EU's Action Plan on Critical Raw Materials (CRMs). Over the course of the project, GREENCAP has developed a CRM-free SC technology achieving battery-like energy densities (>20 Wh/kg, >16 Wh/L), combined with the superior power density and long cycle life characteristic of traditional electrochemical double-layer capacitors. This has been accomplished through the deployment of layered two-dimensional materials (2DMs), including graphene and MXenes, as electrode materials, and ionic liquids (ILs) as high-voltage electrolytes.

In alignment with the EU Green Deal, the project has conducted a comprehensive ex-post environmental, socio-economic, and technological impact assessment. The environmental assessment evaluated the full life cycle of materials and products—including raw material sourcing, manufacturing, and end-of-life management—while the socio-economic assessment examined societal and economic impacts, as well as technological and scientific contributions. These evaluations have provided quantitative evidence for identifying promising business cases and refining strategies for establishing a sustainable industrial value chain around the newly developed SCs.

The ex-post assessment has offered a coherent and evidence-based analysis of GREENCAP's achievements, enabling informed decision-making for researchers, industry partners, policymakers, and other stakeholders. By reflecting on actual project outcomes, this assessment has not only highlighted the environmental and socio-economic benefits of CRM-free supercapacitors but also guided strategic adjustments, enhanced understanding of best practices, and informed pathways for future exploitation and scale-up.

1.2 Impact assessment framework

The GREENCAP ex-post impact assessment has been structured around the Objectives and Key Results (OKR) methodology, a dynamic and interactive framework closely aligned with the project's mission to develop CRM-free supercapacitors that combine battery-like energy density with the superior power density and long cycle life characteristic of traditional electrochemical double-layer capacitors.

Over the course of the project, the OKR methodology has proven to be a crucial tool for monitoring and evaluating progress toward these objectives. Its flexible and results-oriented framework has facilitated the identification of effective strategies, encouraged experimentation, and enabled the exploration of diverse technical solutions. By applying this approach, GREENCAP has not only ensured the achievement of its stated goals but also fostered a culture of high performance, continuous learning, and innovation across the consortium.

The ex-post application of OKRs has provided evidence-based insights into the effectiveness of project activities, guiding strategic adjustments and supporting informed decision-making by researchers, industry partners, and other stakeholders. This assessment demonstrates how the OKR framework has contributed to both the technical advancement of CRM-free supercapacitors and the overall project management and impact evaluation processes.

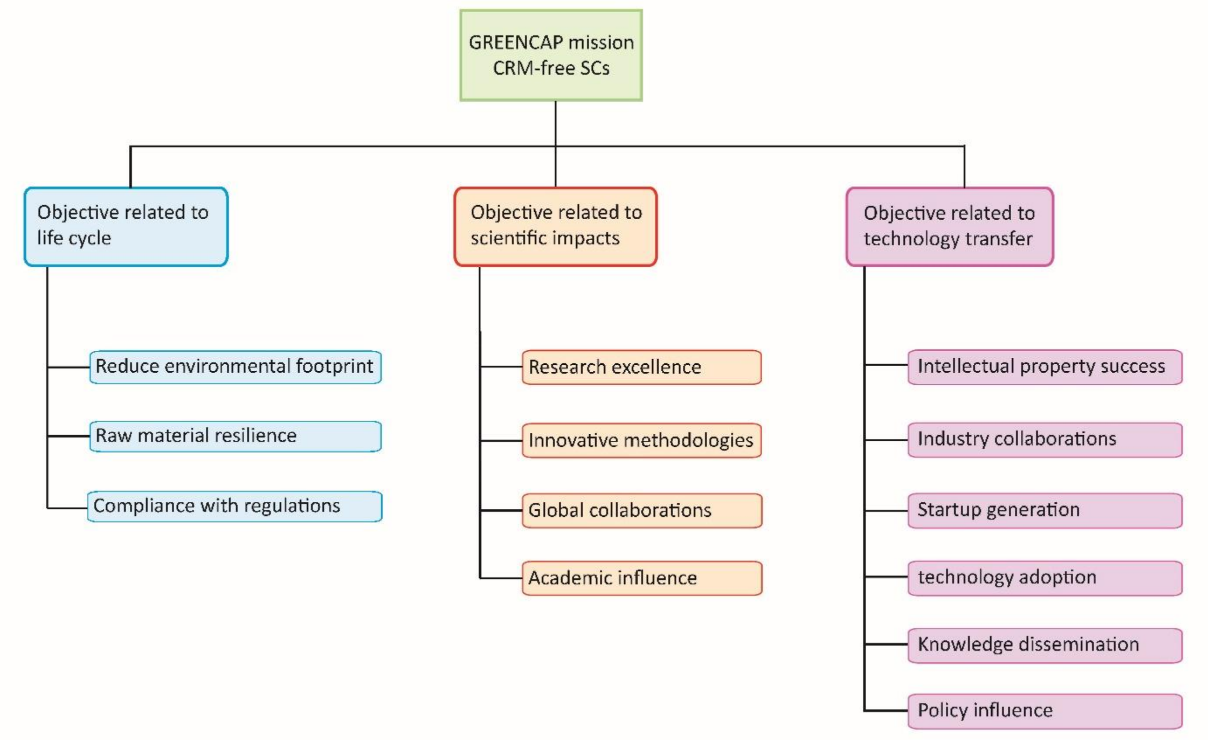


Figure 1. *Impact assessment framework*

Figure 1 illustrates the comprehensive impact assessment framework employed within the GREENCAP project. This framework has been meticulously designed around three fundamental dimensions:

(1) Life Cycle:

The ex-post assessment of the life cycle dimension demonstrates that GREENCAP has successfully advanced toward achieving an environmentally sustainable supercapacitor life cycle. The overarching objective was to minimize environmental impacts across the entire value chain, including raw material extraction, manufacturing, operational use, and end-of-life management. These efforts were carefully aligned with broader sustainability principles and EU environmental goals.

Progress within this dimension has been evaluated based on three key perspectives, providing concrete evidence of the project's environmental performance and guiding improvements in materials selection, manufacturing processes, and waste management strategies. The results highlight the effectiveness of GREENCAP's approach in reducing the ecological footprint of supercapacitors while ensuring compliance with international environmental standards and life cycle assessment methodologies.

- *Reduction of Environmental Footprint: Analyses confirm a measurable decrease in environmental impacts across GREENCAP supercapacitors' life cycle, demonstrating the effectiveness of sustainable material choices and production methods.*
- *Enhancement of Raw Material Resilience: The project successfully mitigated reliance on critical raw materials, increasing supply chain robustness and supporting more resilient and sustainable sourcing strategies.*
- *Adherence to Regulatory Compliance: All materials, processes, and end-products were implemented in full compliance with relevant environmental regulations and international standards, validating GREENCAP's commitment to safe and responsible technology development.*

(2) Scientific Impact Dimension:

The ex-post assessment of the Scientific Impact dimension demonstrates that GREENCAP has significantly advanced the frontiers of knowledge in supercapacitor technology. The primary objective of this dimension was to generate impactful scientific outputs and foster innovation across experimental, computational, and theoretical domains.

Progress has been evaluated through a series of key results, highlighting concrete achievements over the course of the project:

- *Attainment of Research Excellence: GREENCAP produced high-quality scientific outputs, including peer-reviewed publications, conference presentations, and patents, reflecting international recognition and adherence to rigorous research standards.*
- *Pioneering Innovative Methodologies: Novel experimental and analytical approaches were developed, contributing to methodological advancements in the field of electrochemical energy storage.*
- *Cultivation of Global Collaborations: The project successfully established international partnerships with leading research institutions and industry stakeholders, facilitating knowledge exchange and joint research initiatives.*
- *Influence on Academic Spheres: GREENCAP outcomes have had a measurable impact on the academic community, including training of early-career researchers, dissemination of findings, and the shaping of future research directions in sustainable energy storage technologies.*

(3) Technology Transfer Dimension:

The Technology Transfer dimension demonstrates that GREENCAP has effectively facilitated the transition of project innovations from research to practical application. The overarching objective of this dimension was to ensure that developed technologies are successfully implemented, adopted, and valorized across industrial, governmental, and academic domains.

Progress has been evaluated based on the following key results, highlighting tangible achievements:

- *Success in Intellectual Property Endeavors: GREENCAP secured patents, licenses, and other forms of intellectual property, thereby protecting and valorizing project innovations.*
- *Forging Strategic Partnerships with Industry Stakeholders: The project established robust collaborations with companies, consortia, and other entities, enabling the practical implementation and commercialization of developed technologies.*
- *Incubation of Startups: GREENCAP supported the creation and development of spin-offs and new enterprises leveraging project innovations, fostering entrepreneurship and market uptake.*
- *Adoption and Adaptation of Technologies by Industries, Governments, or Entities: Project outcomes have been successfully adopted and adapted by relevant stakeholders, demonstrating real-world applicability and scalability.*
- *Knowledge Dissemination through Training Sessions and Workshops: Capacity building and skills transfer activities were conducted, facilitating the broader utilization of project technologies.*
- *Influencing Policy Decisions: Evidence-based insights generated by the project have informed regulatory frameworks and policy-making related to energy storage technologies and critical raw materials.*

2 Environmental impact assessment

2.1 Goal and scope

2.1.1 Background and objectives

Supercapacitors represent a highly promising class of electrochemical energy storage systems, offering the potential to substantially reduce—or even eliminate—the reliance on critical raw materials, such as lithium (Li), cobalt (Co), and natural graphite, when compared to current market-dominating technologies, including lithium-ion batteries (LiBs). Within the GREENCAP project, layered two-dimensional materials (2DMs), including graphene and MXenes, have been employed as electrode materials, while ionic liquids (ILs) have been utilized as high-voltage electrolytes. The deliberate selection of graphene, MXene, and ILs enables the development of high-energy-density supercapacitors that surpass the performance of state-of-the-art SCs, achieving energy densities comparable to those of LiBs.

The key objectives of this environmental impact assessment are:

- *Providing insight into GREENCAP's environmental performance, identifying both advantages and potential areas of concern.*
- *Demonstrating the robustness of project outcomes through comprehensive sensitivity analyses.*
- *Supplying quantitative data to inform the selection of raw materials and optimize production processes.*

The impact assessment methodology strictly adheres to internationally recognized standards for life cycle assessment, specifically ISO 14040: Environmental Management – Life Cycle Assessment – Principles and Framework and ISO 14044: Environmental Management – Life Cycle Assessment – Requirements and Guidelines. This ensures that the evaluation is both rigorous and comparable with other studies, thereby supporting evidence-based decision-making in materials selection, process optimization, and sustainable technology development.

2.1.2 Functional unit

In this life cycle assessment, one pouch cell is defined as the functional unit, representing the basic energy storage component under evaluation.

2.1.3 System boundaries

Our life cycle assessment is conducted following a cradle-to-gate approach, encompassing all stages from raw material procurement to the formation of the final product, as illustrated in Figure 2.

The environmental impact assessment systematically identified and delineated the key developmental phases of supercapacitor (SC) production and deployment:

- *Production, converting, collection, recycling, and final disposal of the primary base materials used in the primary SC elements from the study systems (manufacturing of SC cell components and manufacturing of SC stack components).*
- *Production, processing, collection, recycling, and final disposal of SC components (electrode manufacturing, cell assembly and formation, stack assembly).*

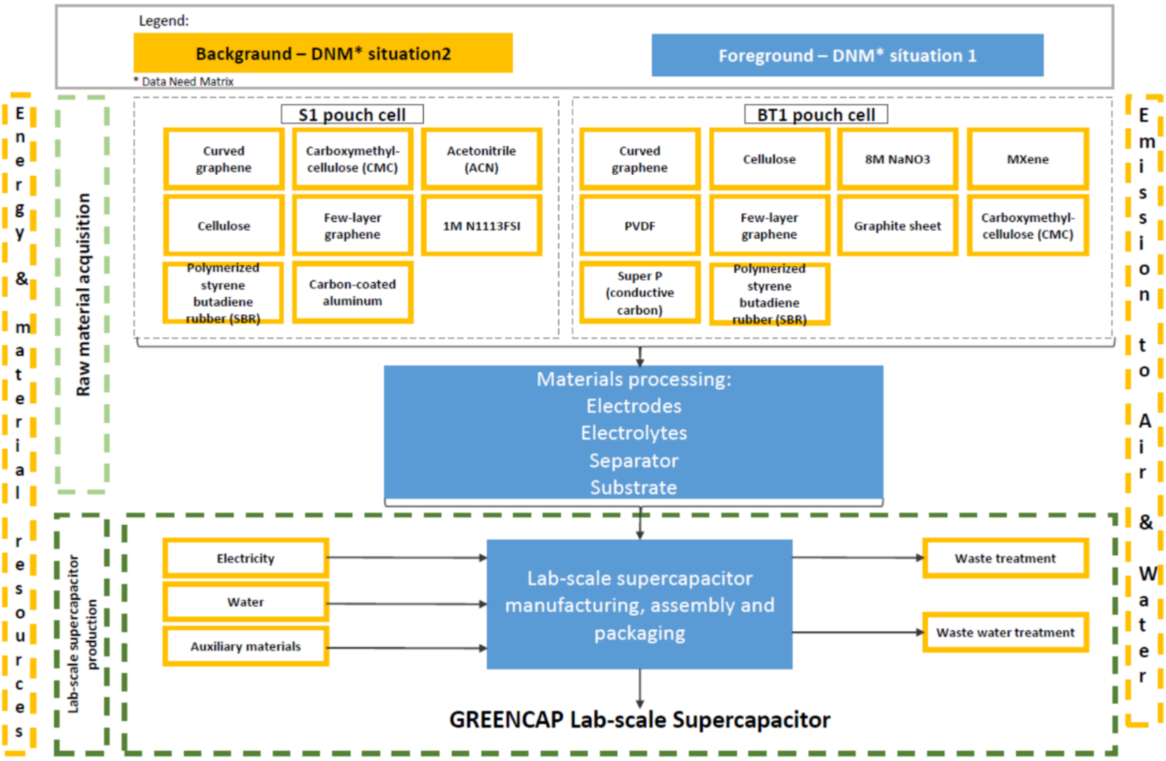


Figure 2. *System boundaries defined for S1 and BT1 pouch cell LCA.*

(Source: Elaborated upon the EU's Product Environmental Footprint Category Rules for Batteries)

The following three situations are included in the Data Need Matrix (DNM), as explained below:

- *Situation 1: The process is run by GREENCAP partners.*
- *Situation 2: The process is not run by GREENCAP partners, and we do not have access to specific information.*

2.2 Environmental footprint impact assessment

2.2.1 Inventory flows

Our comprehensive environmental assessment, grounded in life cycle principles, is based on a thorough identification and quantification of all material and energy flows within the system. The analyzed flows encompass the following*:*

- *raw material intake,*
- *energy consumption metrics,*
- *atmospheric emissions,*

- *emissions into water,*
- *emissions to the ground.*

The inventory of these flows for the system under study is organized into two distinct steps:

- *quantifying all the flows involved in each life cycle stage considered in the impact assessment analysis.*
- *Summing up these flows, which involves linking all steps to the reference flow, i.e., the selected functional unit. In this study, the summarized flows pertain to the production of one pouch cell.*

Following the compilation of these flows, the environmental performance of GREENCAPsupercapacitors is evaluated through the analysis of relevant environmental impact indicators.

2.2.2 Environmental impact indicators

The ex-post environmental footprint assessment of GREENCAP supercapacitors has been systematically conducted to evaluate and elucidate the actual environmental impacts associated with their product life cycles. This assessment utilized well-defined environmental impact categories, with a particular emphasis on midpoint indicators, enabling a focused examination of primary environmental impacts that link specific emissions to their potential adverse effects.

Impact categories were selected in strict accordance with established Life Cycle Assessment protocols, employing models that ensure precision and minimize uncertainty regarding data completeness, quality, and availability. All criteria and methodologies were grounded in the ISO 14040 and ISO 14044 standards, ensuring consistency, transparency, and methodological rigor. While efforts were made to achieve comprehensive coverage, the extent of environmental characterization was necessarily influenced by the quality and resolution of the available inventory datasets.

For clarity and standardization, ISO 14044 terminology was adopted for inventory categories and corresponding indicators. The selected impact categories directly reflect the environmental concerns prioritized in this assessment and are tied to the Life Cycle Inventory (LCI) results for each functional unit. Cumulative outcomes are presented through category indicators, which quantify the realized environmental implications associated with individual functional units, as detailed in Table 1.

This ex-post assessment provides a robust, evidence-based understanding of the environmental performance of GREENCAP SCs, supporting informed decision-making for materials selection, process optimization, and sustainability-driven project development.

Table 1. *Environmental impact indicators*

Impact category	Indicator	Unit
Climate change	Radiative forcing as Global Warming Potential (GWP100)	kg CO_2 eq
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11 eq
Human toxicity, cancer	Comparative Toxic Unit for humans (CTUh)	CTUh
Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTUh)	CTUh
Particulate matter/respiratory inorganics	Impact on human health	disease incidence
Ionising radiation, human health	Human exposure efficiency relative to U235	kBq U^{235} eq
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	kg NMVOC eq
Acidification	Accumulated Exceedance (AE)	mol H^+ eq
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N eq
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N eq
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTUe)	CTUe
Land use	Soil quality index Biotic production Erosion resistance Mechanical filtration Groundwater replenishment	Dimensionless (pt) kg biotic production kg soil m^3 water m^3 groundwater
Water use	User deprivation potential (deprivation-weighted water consumption)	m^3 world eq
Resource use, minerals, and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq
Resource use, fossils	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ

Source: *Assorted by authors upon the EU's Product Environmental Footprint Category Rules for Batteries*

2.3 Life cycle inventory analysis for GREENCAP supercapacitors

2.3.1 Raw material acquisition

To comprehensively evaluate the raw materials employed in GREENCAP supercapacitors, TUD conducted a detailed investigation utilizing five targeted questionnaires. These surveys systematically examined both critical raw materials and CRM-free alternatives, with the collected data analyzed and summarized in Table 2. At this stage of the GREENCAP project, the CRMs incorporated include gallium, aluminium/bauxite, fluorspar, and copper. Gallium is utilized in the synthesis of Mo_2Ga_2C, a key MXene precursor, while aluminium and copper serve as essential components in current collectors, ensuring efficient charge transfer and electrical conductivity. Fluorspar is employed in electrolyte production, contributing to the stability and overall performance of the supercapacitor system. Additionally, the pouch cell casing primarily consists of aluminium, and aluminium/bauxite is used in original equipment manufacturing. The selection of these materials reflects considerations of supplier availability, market dynamics, and specific material performance requirements.

In alignment with GREENCAP's sustainability objectives, ongoing research efforts are focused on identifying and evaluating alternative materials that could reduce or replace reliance on these CRMs. This initiative supports broader environmental and economic goals, enhancing resource efficiency, mitigating supply chain risks, and improving the overall sustainability of supercapacitor technology.

Table 2. *Raw materials used in GREENCAP (Data Collection Period: 01/2023 - 05/2025)*

Components	Critical Raw Materials	CRM-free materials
Electrode (Including every electrode component, as well as the inactive materials)	Gallium, Aluminium/bauxite, copper*	Few-layer graphene, curved graphene, binder (CMC and SBR), activated carbon, PTFE, Ti_3AlC_2, $Ti_3C_2T_x$, Ti_2AlC, Ti_2CT_x, Mo_2Ga_2C, Mo_2CT_x, Ti_3AlCN, Ti_3CNT_x, $(Mo_{2/3}Y_{1/3})_2AlC$, $(Mo_{2/3}Y_{1/3})_2C$, $CuCl_2$, NaCl, KCl, $CuBr_2$, NaBr, KBr, stainless steel, synthetic graphite, PVDF, 3-aminopropyltriethoxysilane
Electrolyte	Fluorspar	Acetonitrile, TEABF4, Pyr13FSI, N1113FSI, Pyr14BF4, Pyr1HTFO, N111HTFO, N111HTFSI, Gamma-valerolactone, Propylene carbonate
Separator		Cellulose, Glass Fiber, Celgard 3501
Casing	Aluminium/bauxite	Stainless steel coin cell parts, polypropylene gasket, aluminium coated stainless steel coin cell parts
OEM (Original Equipment Manufacturer) **BCU** (Battery Control Unit) **BMU** (Battery Management Unit) **SMU** (Safety Management Unit) **ThMU** (Thermal Management Unit)	Aluminium/bauxite	Plastic components, cables

* Copper does not meet the CRM thresholds but is included on the CRM list as *strategic raw material* in line with the Critical Raw Materials Act.[1]

[1] https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en#why-critical-raw-materials-are-important

2.3.2 LCA analysis of S1 pouch cell

Based on the first periodic report on lab-scale supercapacitor development, TUD selected the S1 pouch cells (Table 3) for life cycle assessment analysis and designed a dedicated data collection questionnaire. Defining the system boundary for the S1 pouch cell LCA represents a critical methodological step, as illustrated in Figure 2. The assessment adopts a cradle-to-gate perspective, encompassing all processes from raw material acquisition through to the production of the final lab-scale supercapacitor.

Table 3. *S1 pouch cell*

Acronym	Electrodes	Electrolyte	Separator	Substrate	Mass loading (mg cm^{-2})
S1	CG: FLG: CMCSBR (94:2:4)	N1113FSI/ACN	Cellulose	Carbon coated aluminum	4.72

The environmental impacts of the S1 pouch cell were systematically evaluated across multiple categories using OpenLCA software with Ecoinvent 3.10 database. Summarized results are presented in Table 4. A total of 18 impact categories were analyzed, encompassing key environmental concerns including global warming potential (GWP), resource depletion, ecotoxicity, and human health impacts. This comprehensive assessment provides a robust understanding of the S1 pouch cell's environmental footprint, enabling the identification of critical areas for process optimization and targeted sustainability improvements.

Table 4. *Impact assessment results for the S1 pouch cell*

Impact category	Unit	Result
acidification: terrestrial - terrestrial acidification potential (TAP)	kg $SO_{2\text{-Eq}}$	8.099×10^{-3}
climate change - global warming potential (GWP)	kg $CO_{2\text{-Eq}}$	3.540
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-DCB$_{\text{-Eq}}$	4.437×10^{-1}
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-DCB$_{\text{-Eq}}$	5.753×10^{-1}
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-DCB$_{\text{-Eq}}$	24.472×10^{0}
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg oil$_{\text{-Eq}}$	9.837×10^{-1}
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg P$_{\text{-Eq}}$	3.132×10^{-3}
eutrophication: marine - marine eutrophication potential (MEP)	kg N$_{\text{-Eq}}$	2.418×10^{-4}
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-DCB$_{\text{-Eq}}$	4.956×10^{-1}
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-DCB$_{\text{-Eq}}$	6.278×10^{0}
ionising radiation - ionising radiation potential (IRP)	kBq Co-60$_{\text{-Eq}}$	6.548×10^{-1}
land use - agricultural land occupation (LOP)	m^2*a crop$_{\text{-Eq}}$	9.882×10^{-2}
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu$_{\text{-Eq}}$	3.280×10^{-2}

ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11$_{-Eq}$	$1.726{\times}10^{-6}$
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5$_{-Eq}$	$2.926{\times}10^{-3}$
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg $NO_{x\text{-}Eq}$	$4.884{\times}10^{-3}$
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg $NO_{x\text{-}Eq}$	$5.158{\times}10^{-3}$
water use - water consumption potential (WCP)	m^3	$3.199{\times}10^{-2}$

The global warming potential (GWP) life cycle assessment result for the S1 pouch cell amounts to 3.540 kg CO_2-eq per pouch cell. Since the present study focuses on laboratory-scale prototype cells rather than industrial-scale production, the functional unit is defined as one pouch cell. Once the process is scaled up to industrial production, results can be expressed per kilogram of cell or per kilowatt-hour of capacity for benchmarking with battery-specific frameworks.

Electricity identified as the dominant contributor, accounting for 98.17% of the total GWP, as illustrated in Figure 3. The emission factor for electricity was derived from the country-specific grid mix (location-based approach) as provided in the Ecoinvent 3.10 database.

Given the critical global challenge of climate change, as emphasized in international

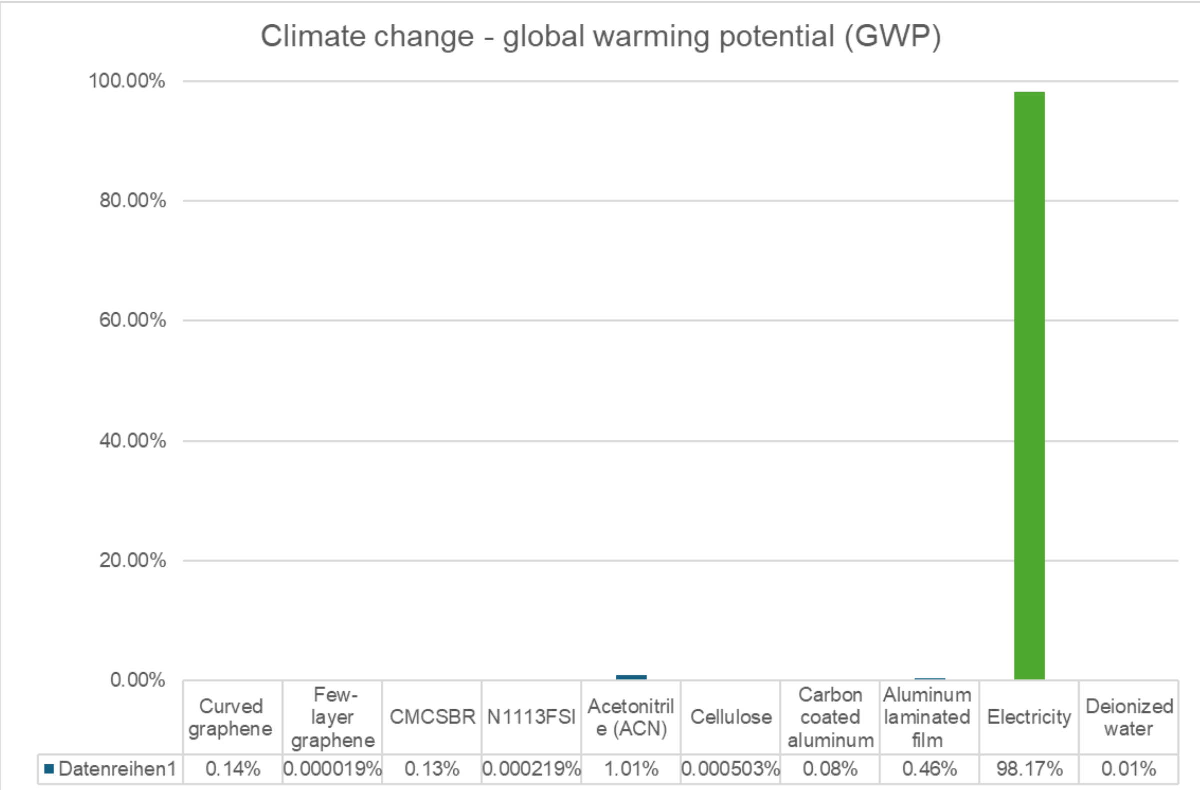


Figure 3. *Analysis of GWP Contributors for S1 pouch cell in %.*

agreements such as the Paris Agreement (2015) and the United Nations Framework Convention on Climate Change (UNFCCC, 1992), addressing GWP is of paramount importance. Regulatory frameworks and sustainability objectives increasingly focus on the reduction of greenhouse gas emissions, reinforcing the necessity to align project activities with these standards. In this context, optimization of energy sources emerges as a key strategy to reduce the environmental footprint of the S1 pouch cell and enhance the sustainability of GREENCAP supercapacitor production.

Figures 4 and 5 display data in ten-thousandths and ten-millionths, respectively, to reveal variations that are not visible when expressed as percentages (Figure 3).

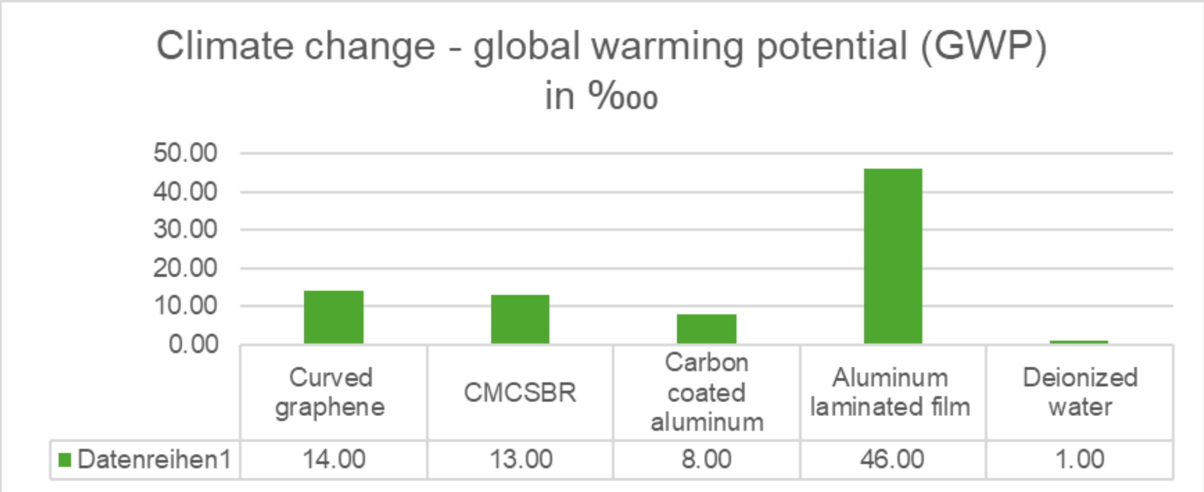


Figure 5. *Analysis of GWP Contributors for S1 pouch cell in ‱*

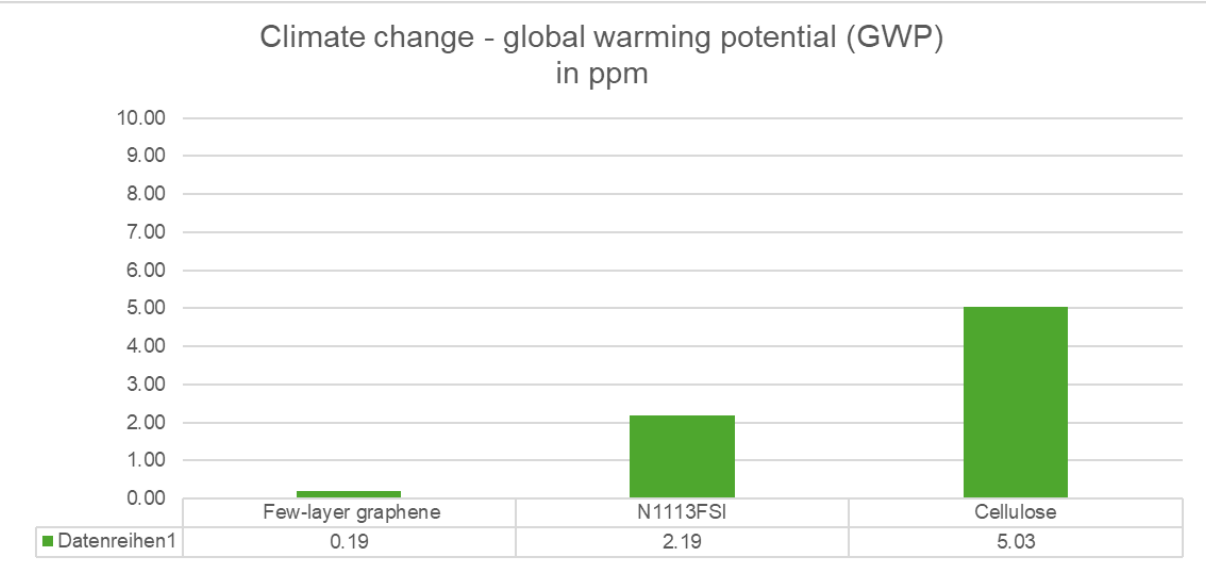


Figure 4. *Analysis of GWP Contributors for S1 pouch cell in ppm*

2.3.3 LCA analysis of BT1 pouch cell

Based on the second periodic report on lab-scale supercapacitor development, TUD selected the BT1 pouch cells (Table 5) for the subsequent life cycle assessment analysis and prepared an updated data collection questionnaire. The BT1 pouch cell represents a new generation of lab-scale devices incorporating MXene-based materials, offering enhanced electrochemical performance and improved energy density. Defining the system boundary for the BT1 pouch cell LCA constitutes a key methodological step, as depicted in Figure 2. Consistent with the previous assessment, a cradle-to-gate approach is applied, covering all stages from the extraction and processing of raw materials—including MXene synthesis—through to the fabrication of the final BT1 pouch cell.

Table 5. *BT1 pouch cell*

Acronym	Electrodes	Electrolyte	Separator	Substrate	Mass loading (mg cm^{-2})
BT1	CG: FLG: CMCSBRMXene:CMCSBR (94:2:4)(80:10:10)	N1113FSI/ACN	Cellulose	Super P (conductive carbon)	2.5

The environmental performance of the BT1 pouch cell was comprehensively evaluated using the OpenLCA software with Ecoinvent 3.10 database, covering 18 environmental impact categories as summarized in Table 6. The assessment encompassed a broad range of environmental aspects, including global warming potential (GWP), resource and energy consumption, ecotoxicity, and human health impacts. This life cycle assessment provides an in-depth understanding of the BT1 pouch cell's environmental footprint and supports the identification of potential opportunities for process optimization and sustainability enhancement.

Table 6. *Impact assessment results for the BT1 pouch cell*

Impact category	Unit	Result
acidification: terrestrial - terrestrial acidification potential (TAP)	kg $SO_{2\text{-Eq}}$	2.600×10^{-4}
climate change - global warming potential (GWP)	kg $CO_{2\text{-Eq}}$	5.483×10^{-2}
ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	kg 1,4-$DCB_{\text{-Eq}}$	1.465×10^{-2}
ecotoxicity: marine - marine ecotoxicity potential (METP)	kg 1,4-$DCB_{\text{-Eq}}$	1.873×10^{-2}
ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	kg 1,4-$DCB_{\text{-Eq}}$	1.071×10^{0}
energy resources: non-renewable, fossil - fossil fuel potential (FFP)	kg $oil_{\text{-Eq}}$	1.425×10^{-2}
eutrophication: freshwater - freshwater eutrophication potential (FEP)	kg $P_{\text{-Eq}}$	6.034×10^{-5}
eutrophication: marine - marine eutrophication potential (MEP)	kg $N_{\text{-Eq}}$	4.198×10^{-6}
human toxicity: carcinogenic - human toxicity potential (HTPc)	kg 1,4-$DCB_{\text{-Eq}}$	6.690×10^{-3}
human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	kg 1,4-$DCB_{\text{-Eq}}$	2.217×10^{-1}

ionising radiation - ionising radiation potential (IRP)	kBq Co-60-Eq	8.000×10^{-3}
land use - agricultural land occupation (LOP)	m^2*a crop-Eq	1.240×10^{-3}
material resources: metals/minerals - surplus ore potential (SOP)	kg Cu-Eq	2.040×10^{-3}
ozone depletion - ozone depletion potential (ODPinfinite)	kg CFC-11-Eq	2.605×10^{-8}
particulate matter formation - particulate matter formation potential (PMFP)	kg PM2.5-Eq	9.627×10^{-5}
photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	kg NO_{x}-Eq	1.100×10^{-4}
photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	kg NO_{x}-Eq	1.100×10^{-4}
water use - water consumption potential (WCP)	m^3	4.100×10^{-4}

The global warming potential (GWP) of the BT1 pouch cell was calculated as 5.483×10^{-2} kg CO_2-eq per functional unit, significantly lower than that of the S1 pouch cell. Similar to the S1 configuration, electricity consumption was identified as the primary contributor to total GWP, underscoring the pivotal role of energy use in determining the overall carbon footprint of cell manufacturing.

This relatively low GWP value demonstrates the improved energy efficiency and reduced material intensity of the BT1 design. Nevertheless, further emission reductions could be achieved through the integration of renewable electricity sources and process energy optimization. Such strategies are aligned with global efforts to mitigate climate change as established in the Paris Agreement (2015) and the UNFCCC (1992) frameworks.

By targeting reductions in energy-related emissions and enhancing resource efficiency, the BT1 pouch cell offers a promising pathway toward a more sustainable and low-carbon production model within the GREENCAP supercapacitor series.

The contribution analysis of global warming potential (GWP) for the BT1 pouch cell is illustrated in Figure 6. Among all input materials and processes, electricity consumption is identified as the dominant contributor, accounting for 53.72% of the total GWP. This emphasizes that the energy-intensive nature of the manufacturing process remains the primary driver of carbon emissions in BT1 cell production. The aluminum laminated film also presents a significant impact, contributing 32.97% to the overall GWP. This impact is mainly associated with the high energy requirements and carbon intensity of aluminum production. The use of advanced nanomaterials such as Mxene (5.16%) and curved graphene (4.33%) also exerts a moderate influence on the total GWP, primarily due to their complex synthesis and purification processes. Other components—including CMC/SBR binder (0.07%), $NaNO_3$ electrolyte (2.84%), graphite (0.81%), PVDF (0.03%), and deionized water (0.002%)—show relatively minor contributions, indicating effective material efficiency in these subsystems.

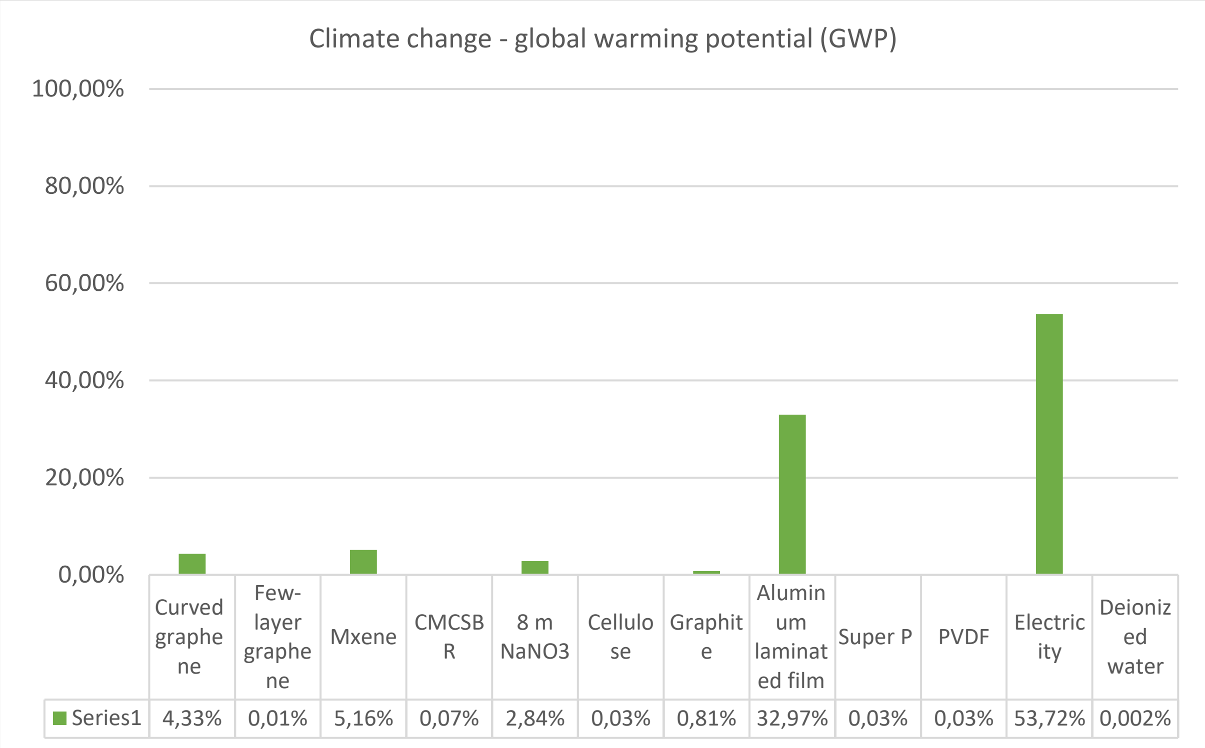


Figure 6*. Analysis of GWP Contributors for BT1 pouch cell*

The overall results highlight that reducing the carbon intensity of electricity supply and improving material production efficiency—particularly for aluminium and nanomaterials—are key strategies to further minimize the carbon footprint of the BT1 pouch cell.

2.3.4 Comparative Analysis of Environmental Impacts between S1 and BT1 Pouch Cells

While the S1 pouch cell already demonstrates strong performance and favorable environmental characteristics, the BT1 configuration achieves even more significant improvements across nearly all impact categories. Both systems were analyzed under identical cradle-to-gate boundaries, encompassing processes from raw material extraction to final cell assembly. However, BT1's incorporation of MXene-based materials, optimized electrode formulation, and reduced mass loading has led to substantial reductions in environmental impacts.

As summarized in Tables 4 and 6, the global warming potential (GWP) of the BT1 pouch cell decreased dramatically from 3.540 kg CO_2-eq (S1) to 0.05483 kg CO_2-eq, corresponding to a reduction of approximately 98.45%, reflecting the enhanced energy efficiency and optimized processes of the BT1 design. Similar trends are observed across other key categories:

- *Terrestrial acidification potential (TAP) decreased by ~96.8% (from 8.099×10^{-3} to 2.600×10^{-4} kg SO_2-eq).*

- *Fossil fuel depletion (FFP) fell by ~98.5% (from 9.837×10^{-1} to 1.425×10^{-2} kg oil-eq).*
- *Freshwater ecotoxicity potential (FETP) and marine ecotoxicity potential (METP) declined by approximately 96–97%.*
- *Human toxicity potentials (carcinogenic and non-carcinogenic) were reduced by over 95%, reflecting improvements in material selection and cleaner synthesis routes.*
- *Water consumption potential (WCP) dropped from 3.199×10^{-2} to 4.1×10^{-4} m^3, representing a 98.7% reduction, indicating efficient solvent management and lower resource intensity*

In both S1 and BT1 pouch cells, electricity consumption remains the dominant GWP contributor, highlighting the central importance of energy source decarbonization.

- *For S1, electricity accounted for 98.17% of total GWP, underscoring the high energy demand of lab-scale processes.*
- *For BT1, this share decreased to 53.72%, signifying substantial improvements in process energy efficiency and optimized operational protocols.*

The comparative analysis demonstrates that the BT1 pouch cell not only enhances electrochemical performance but also represents a major environmental advancement. The marked reduction in energy- and material-related impacts validates the design's alignment with the sustainability objectives of the Paris Agreement (2015) and the UNFCCC (1992), promoting a low-carbon manufacturing trajectory for future GREENCAP products.

Overall, both S1 and BT1 pouch cell demonstrate a comprehensive environmental improvement across all evaluated impact categories. These results confirm that targeted process optimization, material substitution, and energy structure transformation can effectively mitigate the environmental footprint of supercapacitor production. Consequently, the S1 and BT1 pouch cell represent a more sustainable and climate-resilient design, aligning with the overarching goals of low-carbon manufacturing and green energy technology development under the GREENCAP project framework.

3 Socio-economic impact assessment

3.1 Goal and Scope

3.1.1 Background and objectives

Critical raw materials hold strategic significance for the European Union (EU) economy and its diverse industrial sectors due to their high supply risks and substantial economic importance. These materials are indispensable across numerous industries and technologies, underpinning the EU's competitive advantage and supporting environmental sustainability objectives. CRMs play a pivotal role in European economic development, technological innovation, and the achievement of long-term sustainability goals.

The EU has long recognized the strategic importance of CRMs. Initiatives such as the Critical Raw Materials Action Plan, established in 2011, were designed to address challenges associated with supply security and responsible sourcing. Given the evolving geopolitical, economic, and technological landscape, the EU continues to update the CRM list periodically, reflecting shifts in material significance and supply risk. This dynamic process underscores the EU's commitment to proactive management and adaptation within the global materials market.

In this context, the GREENCAP project's efforts to develop CRM-free supercapacitors have aimed to enhance raw material resilience. By reducing reliance on CRMs, which are vulnerable to supply disruptions and price volatility, GREENCAP SCs contribute to strengthening supply chain robustness while simultaneously supporting sustainability and circular economy principles.

The ex-post socio-economic impact assessment evaluates the realized implications of GREENCAP SCs with a particular emphasis on raw material resilience. The analysis highlights how CRM-free SCs contribute to the EU's economic stability, industrial competitiveness, and sustainable development objectives, thereby providing evidence-based insights into the broader socio-economic benefits of transitioning to resilient and sustainable energy storage technologies.

3.1.2 Assessment scope and indicators

A comprehensive ex-post socio-economic impact assessment was conducted to evaluate the realized socio-economic effects of GREENCAP products. This assessment systematically examined well-defined impact categories, which were organized into two primary dimensions: scientific impacts and technology transfer impacts. This distinction is particularly pertinent to the development of CRM-free supercapacitors, a field in which GREENCAP has demonstrated pioneering advancements, as detailed in Table 7.

The assessment placed special emphasis on the resilience of raw materials employed in SC production and their role in enhancing the social and economic sustainability of the EU. By examining both scientific contributions and technology transfer outcomes, the ex-post analysis provides evidence-based insights into how GREENCAP products have influenced research excellence, industrial uptake, and broader socio-economic benefits, including supply chain robustness, resource efficiency, and alignment with circular economy principles.

3.2 Scientific impacts

3.2.1 Scientific inputs

GREENCAP is focused on advancing the technology and science of SCs. As such, this creates an environment in which investment plays a key role along with people to achieve the step change needed to drive activities forward. In this section, the inputs driving our scientific developments encompass a substantial investment of 5,425,360 Euros. This investment fuels a collaborative effort that brings together the expertise and resources of 5 esteemed universities, along with the research capabilities of 1 leading R&D institute and the innovative prowess of 5 forward-thinking companies. Together, this collective force represents a diverse and dynamic network dedicated to advancing scientific knowledge and driving innovation.

Table 7. *Focus areas and indicators of the socio-economic impact assessment*

Areas	Indicators
Scientific impact	Number and quality of research publications.
	Advancements or modifications in scientific theories or methodologies.
	Research collaborations formed.
	Influence on academic curricula or training programs.
Impacts on technology transfer	Licensing of technologies or intellectual property.
	Collaborations or partnerships with industries.
	Spin-offs or startups emerging from the research.
	Adoption or adaptation of technologies by industries, governments, or other entities.
	Training sessions or workshops aimed at introducing new technologies to potential users.
	Influence on policy decisions or regulations based on the technology developed.

3.2.2 Scientific activities

Within the GREENCAP project, significant progress has been achieved in the development of electrode materials that eliminate reliance on critical raw materials. Graphene- and MXene-based electrodes have been successfully synthesized from CRM-free precursors using environmentally benign methods, effectively avoiding the use of toxic or hazardous chemicals.

Parallel efforts in sustainable electrolyte development have yielded notable advancements. High-voltage ionic liquids (ILs) have been successfully synthesized, including Pyr13FSI, N1113FSI, Pyr14BF4, 1M Pyr14BF4 in ACN, 1M N1113FSI in ACN, EMIFSI, N111HTFO-Trimethylammonium triflate (hydrophilic), N111HTFSI-Trimethylammonium and (trifluoromethanesulfonyl) imide (hydrophobic), Pyr1HTFO-N-methylpyrrolidinium triflate (hydrophilic). These innovations contribute both to the environmental sustainability and the enhanced electrochemical performance of GREENCAP supercapacitors.

The ex-post assessment confirms that these developments have successfully delivered CRM-free and environmentally friendly materials, representing a critical step toward sustainable, high-performance supercapacitor technology.

3.2.3 Scientific outputs and impacts

(1) Innovative SC management systems (SMSs)

The GREENCAP supercapacitor (SC) technology has demonstrated significant progress in eliminating the need for complex thermal and energy management systems, which are typically required for conventional batteries. This “fit-and-forget” approach enhances operational safety while reducing maintenance requirements. The intrinsic characteristics of SCs—low risk of parasitic side reactions and minimal heat generation during charging and discharging—support this simplification of system management.

Through the integration of novel state-of-charge (SoX) monitoring tools and refined supercapacitor management systems (SMS), GREENCAP has successfully optimized the performance of electrochemical double-layer capacitors (EDLCs). These refinements allow for the prevention of reverse polarity and ensure the safe operation of SCs, while simultaneously maximizing energy and power density. Ex-post evaluation confirms that these advancements contribute to the long cycle life of GREENCAP SCs (>10^6 cycles), demonstrating the effectiveness of the technology in achieving high-performance, durable, and low-maintenance energy storage solutions.

(2) Publications and conferences

Although GREENCAP is fundamentally centered on materials innovation, the initial project period has already demonstrated significant research activity and socio-economic engagement. During the first eight months, intensive materials research was conducted, marking a highly productive phase in the development of CRM-free supercapacitor technologies.

The ex-post socio-economic assessment indicates that project activities—including peer-reviewed publications, conference presentations, and participation in collaborative meetings—progressed steadily during this period, with a notable increase following the first six months. This trend aligns with the typical trajectory observed in large-scale collaborative research projects, which generally gain momentum as preliminary results are produced and disseminated.

Ex-post evaluation further confirms that GREENCAP partners actively contributed to these outcomes, as evidenced by monthly project meetings, documented publications, and recorded participation in workshops and conferences. These activities collectively highlight the consortium's commitment to advancing scientific knowledge, fostering collaboration, and generating socio-economic value in the early phases of the project.

(3) Contribution of GREENCAP to foster collaboration in research and innovation

The GREENCAP project exemplifies a successful multinational and multi-institutional collaboration, uniting researchers from diverse countries and organizations. This collaborative framework has produced multiple advantages, including the pooling of expertise and resources, the avoidance of duplicative research efforts, and the facilitation of coordinated project activities.

By integrating specialists from a variety of scientific and industrial backgrounds, GREENCAP has advanced its technical objectives while simultaneously contributing to broader European excellence and capacity-building initiatives. Ex-post assessment indicates that the project's activities have played a significant role in supporting EU policy objectives, fostering international collaboration, and generating measurable economic and social benefits.

The consortium's sustained commitment to cooperation demonstrates GREENCAP's dedication to promoting scientific excellence, technological innovation, and positive socio-economic impacts within the EU. These outcomes underscore the strategic value of collaborative research initiatives in driving both technological advancement and the overarching goals of European sustainability and competitiveness.

3.3 Impacts on technology transfer

3.3.1 Technology transfer inputs

The principal drivers of technology transfer within the GREENCAP project are financial investment and the dedicated personnel contributing to project activities. Ex-post evaluation indicates that the inputs supporting technology transfer align closely with those allocated for scientific research, reflecting the integrated nature of knowledge generation and its subsequent application.

These combined resources have been instrumental in facilitating the effective dissemination, adoption, and valorization of GREENCAP innovations, ensuring that technological outcomes are transferred efficiently from research to practical implementation across industrial and societal domains.

3.3.2 Technology transfer activities

GREENCAP's efforts in technology transfer are evidenced by its various communication and engagement activities. Key highlights since January 2023 include the launch of the project website (in March 2023), engagement on LinkedIn, and dissemination of project outcomes.

- *Project website launch: greencap-project.eu, featuring 50 news/events updates.*
- *As of October 2025: over 17000 website views and over 4300 unique visitors.*
- *A growing LinkedIn presence with 378 followers.*

Figures 7 offers visual data related to these platforms.[2] [3]

Analysis of GREENCAP project outreach indicates that its activities have successfully engaged a diverse range of stakeholders. The primary audience comprises academic researchers, followed by professionals from strategic management services, appliances, electrical and electronics manufacturing, electrical equipment manufacturing, and chemical manufacturing, demonstrating early and active engagement of key target groups.

Furthermore, data from LinkedIn and the project website reveal that GREENCAP's progress is monitored by stakeholders across all EU countries, with a notable presence of interested parties in the United States. These engagement metrics are continuously reviewed and updated in coordination with dissemination, communication, and exploitation activities, ensuring alignment with the evolving outreach strategy and maintaining relevance for the broader scientific, industrial, and policy-making communities.

[2] https://greencap-project.eu/

[3] https://www.linkedin.com/company/greencap2023/about/?viewAsMember=true

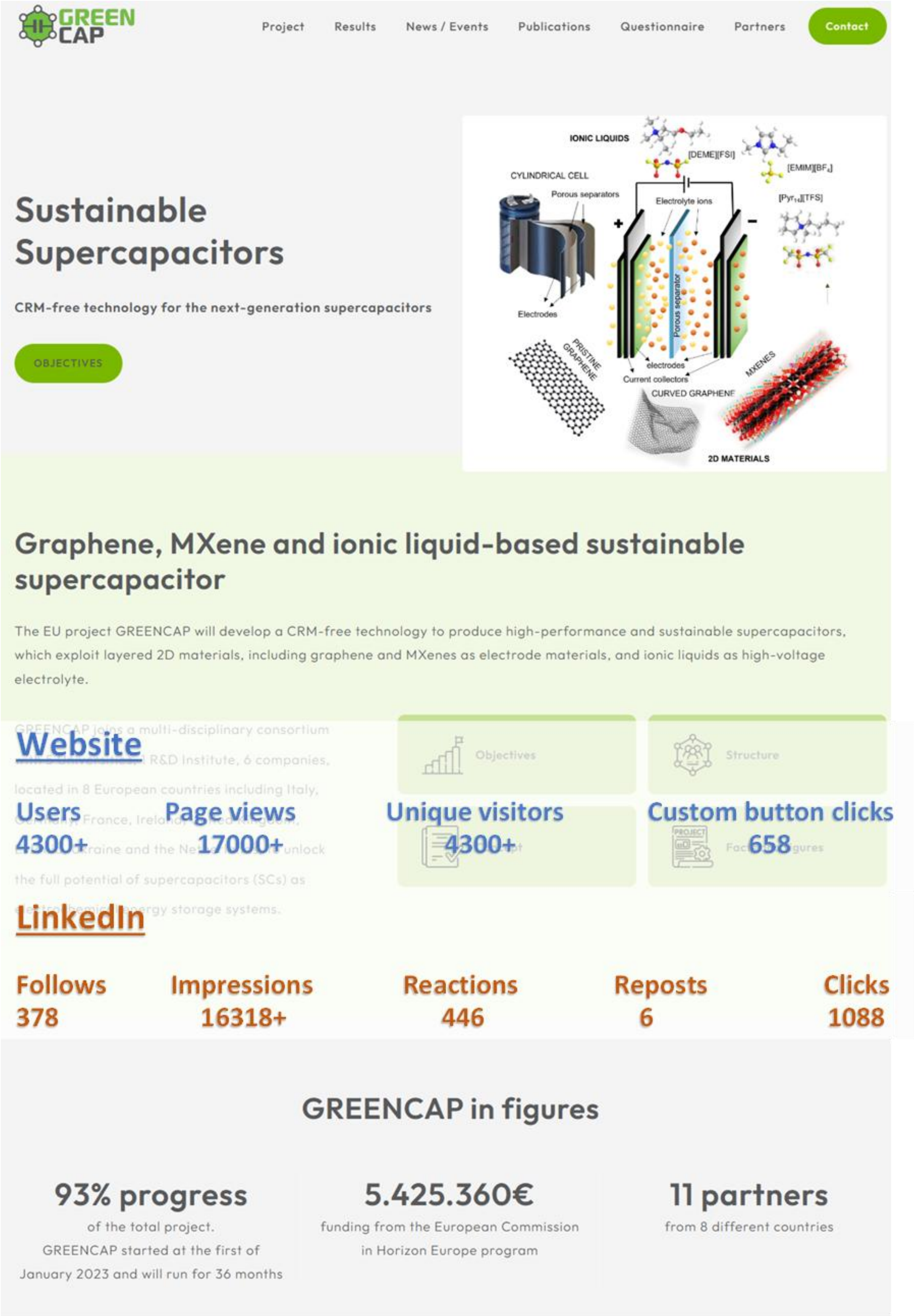


Figure 7. *Press and media activities*

3.3.3 Technology transfer outputs and impacts

Based on the analysis of questionnaires presented in Section 2, the GREENCAP project demonstrates a strong emphasis on sourcing raw materials within European boundaries. This strategic approach aligns closely with GREENCAP's core initiatives while simultaneously supporting broader EU objectives aimed at enhancing resource efficiency and supply chain resilience.

The ex-post assessment highlights several key outcomes of this localized sourcing strategy. First, it ensures a reliable and secure supply of raw materials, which constitutes a fundamental pillar for the successful development of GREENCAP supercapacitors. Second, it significantly contributes to the EU's sustainability goals by minimizing the carbon footprint associated with material transportation and reinforcing principles of environmental responsibility. Third, this approach enhances economic resilience within the EU, supporting local industries and businesses engaged in the extraction, production, and distribution of raw materials, thereby contributing to economic growth and stability.

Overall, GREENCAP's commitment to localized and sustainable raw material sourcing exemplifies best practices in technology transfer while advancing the EU's objectives of fostering a green, sustainable, and resilient economy.

3.4 Social market research

3.4.1 First Socio-economic assessment questionnaire

A comprehensive socio-economic impact assessment was conducted to analyse the broader socio-economic implications of GREENCAP products. As part of this effort, TUD has carried out the first socio-economic impact survey, detailed in Table 8. The first survey consisted of nine targeted questions designed to capture industry perspectives on supercapacitor applications, costs, advantages, and challenges.

The responses indicate that supercapacitors have diverse application areas, including public transportation, heavy transport, automotive, smart grids, and industrial machinery. Additionally, their cost remains high, and due to confidentiality concerns, no data was provided on annual sales volumes. However, supercapacitors are recognized as a more cost-effective energy storage solution compared to other technologies.

Key advantages identified by purchasers include high energy efficiency, fast charging/discharging capabilities, long lifespan/ durability, and low maintenance requirements. However, the main drawbacks are their limited energy storage capacity and high upfront costs. Future potential improvements in supercapacitor technology could enhance their performance by increasing energy storage capacity, improving charge/discharge speeds, extending durability and service life, reducing size and weight, and enhancing cost-effectiveness.

Table 8. *First survey for socio-economic impact analysis*

No	Question	Feedback
1	Which sectors are the primary customers of your company's supercapacitors?	Heavy transportation, Cars, Public transportation, Industrial machinery, Smart grids, Industrial machinery
2	What is the average annual sales volume range?	
3	Could you provide a price range for different products' costs and profit margins?	(1) Supercapacitors, Cost: < 5,000, profit: < 2,000 (€/kWh) (2) Supercapacitor modules, Cost: 5,000 – 10,000, profit: 2,000 – 5,000 (€/kWh) (3) Supercapacitor systems, Cost: > 15,000, profit: > 7,500 (€/kWh)
4	How would you rate the overall cost-effectiveness of supercapacitors compared to other energy storage solutions?	Much more cost-effective
5	Have purchasers provided feedback regarding their satisfaction with the use of supercapacitors? If so, what are the primary strengths and weaknesses they have identified?	**Strengths:** High energy efficiency, Fast charging/discharging capability, Long lifespan/durability, Low maintenance requirements **Weaknesses:** Limited energy storage capacity, Higher upfront costs
6	In what ways could the development of supercapacitors enhance the performance of existing supercapacitors? Additionally, in which areas could these improvements lead to new growth opportunities?	**Potential Improvements:** Increased energy storage capacity, Faster charge/discharge cycles, Enhanced durability and lifespan, Reduced size and weight, Improved cost-effectiveness **Growth Opportunities:** Expanding into new markets, Enabling new applications, Strengthening competitive positioning in existing markets, Supporting the development of more sustainable/eco-friendly products
7	How do you foresee the demand for supercapacitors evolving in the next 5 years?	Significant increase
8	What challenges does your company face in integrating supercapacitors into existing systems or products?	Regulatory hurdles, High initial investment costs
9	Which external factors could significantly impact the adoption and deployment of supercapacitors in industry?	Technological advancements, Changes in energy prices

These technological improvements are expected to drive new growth opportunities by expanding markets, enabling novel applications, strengthening competitive positioning, and supporting the development of more sustainable and environmentally friendly products. The demand for supercapacitors is projected to rise significantly over the next five years.

However, several challenges remain in integrating supercapacitors into existing systems and products, including regulatory barriers and high initial investment costs. Additionally, external factors such as technological advancements and fluctuations in energy prices may significantly influence the adoption and deployment of supercapacitors within the industry.

3.4.2 Second Socio-economic assessment questionnaire

Building on the results of the first socio-economic assessment questionnaire and subsequent developments in supercapacitor technology, a second version of the questionnaire (Table 9) was developed to address additional dimensions, including market acceptance, technical maturity, economic feasibility, policy frameworks, and environmental impact. The surveys provided comprehensive insights into the prospects and challenges associated with graphene-based supercapacitors.

The assessment indicates that graphene-based SCs possess substantial potential for future market applications, driven primarily by their competitive performance characteristics, favorable cost structure of graphene, and increasing global attention to environmental sustainability. However, respondents consistently noted that technical maturity remains limited. Key areas requiring improvement include energy density, cycle life, and manufacturing complexity, which are critical prerequisites for successful market entry.

From an economic feasibility perspective, the primary barrier to large-scale production lies in the complexity and energy intensity of manufacturing processes, resulting in high costs that currently impede commercial adoption. Expert feedback suggests that 2–5 years of sustained R&D will be necessary to overcome these challenges, emphasizing the need for close collaboration between research institutions and industry to exploit the unique material properties of graphene for niche applications.

Regarding policy measures, respondents highlighted public infrastructure applications as the most promising pathway for accelerating commercialization. Recommendations included government-led initiatives, such as incentives or mandates for the adoption of SC technology in the transportation sector, and potential fiscal incentives to stimulate market demand among end-users.

Environmental considerations were emphasized as a critical factor for commercialization, with respondents identifying three primary areas of concern:

- *Toxicity and biological effects of nanomaterials: The long-term ecological and biocompatibility implications of graphene remain insufficiently studied.*

- *Energy intensity during production: High energy consumption in manufacturing may offset potential life-cycle carbon benefits.*
- *Use of hazardous chemicals: Risks associated with solvents or by-products during synthesis require stringent control measures.*

The consensus among respondents was that a comprehensive Life Cycle Assessment is essential prior to commercialization to evaluate environmental trade-offs and mitigate potential ecological liabilities. OngoingCA efforts are regarded as both scientifically valuable and critical for pre-emptive risk management.

Overall, the analysis demonstrates that graphene-based SCs have gained significant attention in the scientific and industrial communities, with promising application potential and environmental advantages. Nevertheless, the current technological readiness level remains insufficient for immediate commercial deployment, indicating that approximately a decade of further technical refinement and enhanced market acceptance will be required. Advancing this technology demands a multidimensional approach, integrating R&D, policy support, and market engagement.

Table 9. *Second survey for socio-economic impact analysis*

Section	No	Question	Feedback
Market acceptance	1	Which factor do you believe most strongly drives the market adoption of these innovative supercapacitors?	Performance improvements from advanced materials.
	2	How do you perceive the overall potential demand for sustainable supercapacitor technologies across various sectors?	High demand in select sectors.
Technical Maturity	3	How would you rate the current technical maturity of graphene and MXenebased supercapacitor technology applications?	Moderately developed, with significant R&D still required.
	4	What do you believe is the most critical technical challenge that needs to be overcome for successful development of graphene and MXene-based supercapacitors?	Scalable and cost-effective production methods.
	5	Which technical enhancement do you consider most critical for advancing the commercialization of these materials?	Increased energy density.

Economic Feasibility	6	What do you consider the most significant economic barrier to scaling up production of graphene and MXene-based supercapacitors?	Complex and energy-intensive manufacturing processes.
	7	How would you assess the commercial viability timeframe for graphene and MXene-based supercapacitors?	Medium-term (3-5 years).
	8	What do you believe would be the most effective approach to improve the economic feasibility of graphene and MXene-based supercapacitors?	Industrial partnerships and joint ventures.
Policy Requirements	9	Which EU-level policy instrument would most effectively support the development and deployment of graphene and MXene-based supercapacitors?	Regulatory frameworks favoring critical raw material-free technologies.
	10	How do you perceive the impact of the EU's Critical Raw Materials Act on the potential success of the GREEPCAP project?	Highly positive - creates clear market opportunities. Moderately positive - provides some supportive framework.
	11	What type of policy support do you believe would most accelerate the market adoption of graphene and MXene-based supercapacitors?	Projects in public infrastructure.
	12	Which policy initiative would most effectively promote collaboration and innovation in this field?	Joint public–private research funding programs.
Environmental Impact	13	What do you consider the most significant potential environmental benefit of graphene and MXene-based supercapacitors?	Elimination of critical raw materials and associated mining impacts. Longer operational lifetime reducing replacement frequency. Enhanced energy efficiency in applications.
	14	Which potential environmental risk associated with graphene and MXene materials production and use concerns you most?	Nanomaterial safety and potential toxicity.

	15	How important do you consider life cycle assessment in guiding the development of graphene and MXene-based supercapacitors?	Important after proof of concept but before commercialization.
Demographic Information	16	Which of the following best describes your professional role?	Academic researcher.
	17	What is your primary field of expertise?	Energy storage/supercapacitor technology.
	18	How many years of experience do you have in fields related to energy storage or advanced materials?	6-10 years.

3.4.3 Third Socio-economic assessment questionnaire

The third GREENCAP survey was developed as part of the Supercapacitor Socio-Economic Impact Assessment, marking a shift from purely technical evaluations toward public engagement. The first two surveys had been conducted internally by GREENCAP partners, focusing on expert benchmarking of state-of-the-art devices. By contrast, this third survey was the first public-facing questionnaire, designed to gather insights from a broader audience regarding the priorities for future supercapacitor development.

Following our benchmarking activities, the D60 form has been selected for use in the GREENCAP project. Accordingly, all subsequent references to supercapacitors in this survey will specifically concern the Skeleton Technologies D60 form.

As shown in Table 10 and Figure 8, the GREENCAP prototype demonstrated substantial improvements over the global state-of-the-art and Skeleton benchmarking in terms of energy density (+22.9%) and capacitance (+32.35%), as well as a promising trajectory in cost reduction potential. However, challenges were also evident: the prototype exhibited a shorter cycle life (-65%), a slightly higher ESR (+22.8%), and a marginally lower rated voltage (-5%).

To contextualize these findings, the survey presented respondents with both the benchmarking data and visual comparisons, and then asked a central question: “In light of the above data, which aspects require further improvement?” Respondents were able to choose from options such as higher energy density, longer cycle life, faster charging speed, larger capacitance, lower cost, or suggest their own priorities.

The analysis of the 65 valid responses collected through the GREENCAP public survey provides a comprehensive view of general population expectations regarding the future trajectory of supercapacitor development (Figure 9). A dominant 88% of respondents expressed that longer cycle life represents the most critical performance parameter requiring improvement, clearly positioning device durability as the central determinant of technology adoption and long-term competitiveness.

Table 10. Performance of Supercapacitor Prototype Products

KPI	Parameter	Unit	Global State-of-the-art	Skeleton Benchmarking	GREENCAP Prototype
1	Energy density	Wh/L	10.60	10.90	13.40
2	ESR 1s	mOhm	0.23	0.21	0.258
3	Cycle life	Cycles	1,000,000	1,000,000	350,000
4	Capacitance	F	3,400	3,400	4,500
5	Rated voltage	V	3.0	3.0	2.85

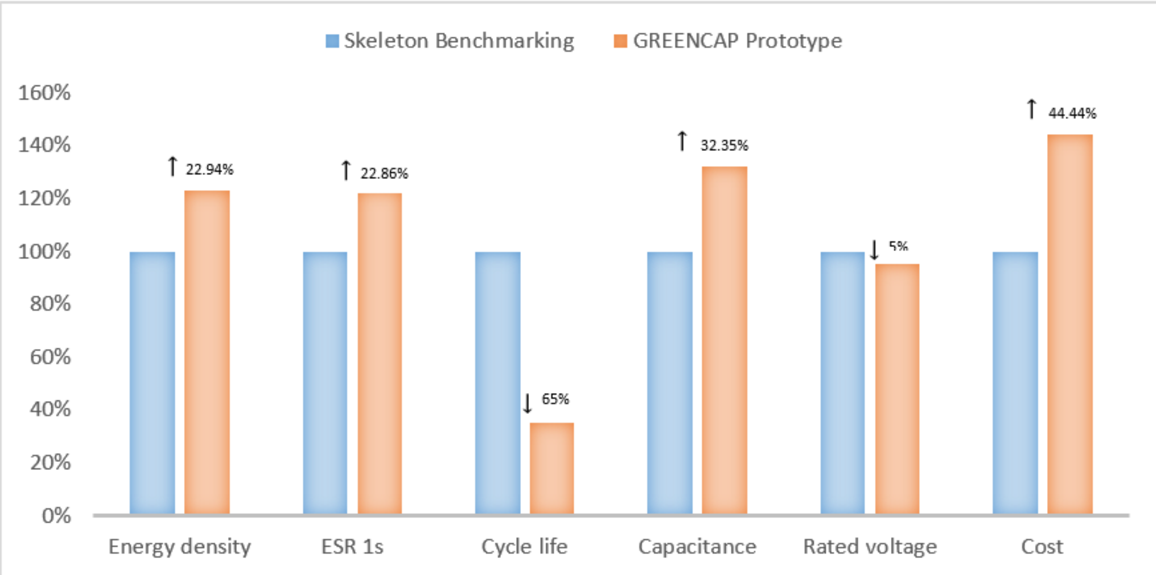


Figure 8. *Comparison between Benchmarking and the GREENCAP Prototype*

Closely following this, 65% of participants emphasized lower cost as a priority, reaffirming that economic accessibility remains a decisive factor for the successful commercialization of emerging energy storage technologies.

While these two aspects emerged as the most salient themes, additional performance dimensions were also highlighted. Approximately one quarter of respondents (20%) selected faster charging speed, and 18% indicated larger capacitance as desirable directions for further enhancement, reflecting an interest in improving both user experience and storage capability, though with less urgency compared to lifetime and cost. Notably, only 8% of the surveyed group identified higher energy density as a key area for development, suggesting that the current prototype improvements in this metric are already perceived as adequate or exceeding baseline expectations. Beyond the predefined options, several respondents explicitly pointed to the importance of addressing ESR and rated voltage, thereby drawing attention to the operational stability and efficiency of the devices under realistic usage conditions.

Overall, these results highlight a nuanced set of general population priorities: while advancements in energy density and capacitance are recognized as valuable achievements, they are not perceived as the most pressing concerns. Instead, the survey underscores that future R&D efforts should be strategically directed toward enhancing cycle life and reducing production costs, complemented by targeted improvements in charge–discharge performance and stability parameters. Such a focus would not only address the immediate barriers identified by potential end-users but also strengthen the readiness of supercapacitor technologies for large-scale integration across di verse application sectors.

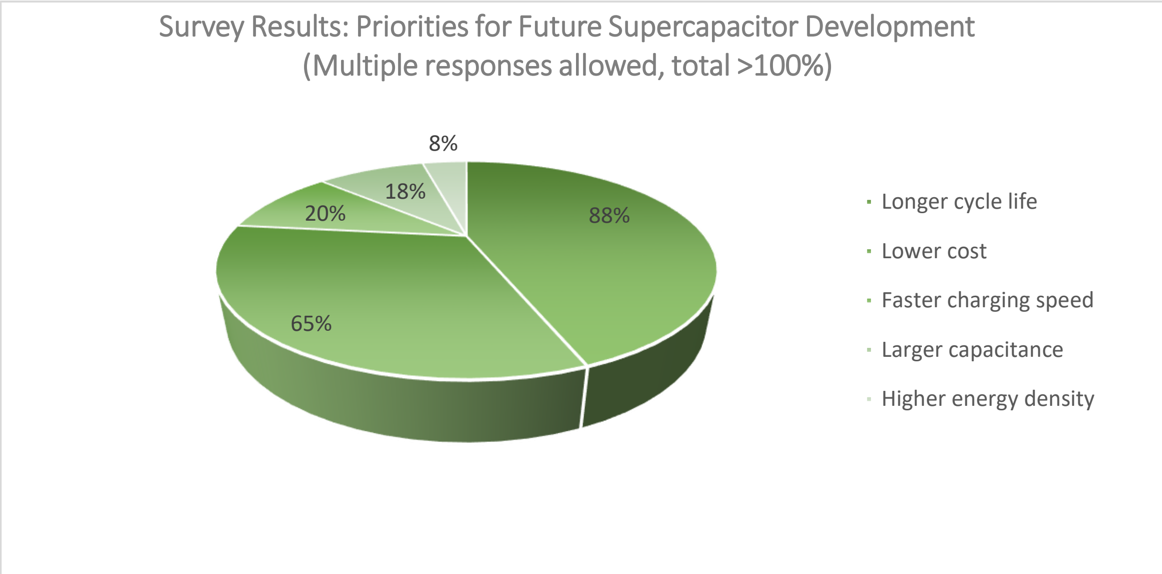


Figure 9. *Distribution of Respondent Priorities in the GREENCAP Public Survey*

4 Conclusion and Outlook

The GREENCAP project has achieved remarkable and measurable progress in the development of critical raw material-free supercapacitors, positioning itself at the forefront of sustainable energy storage innovation in Europe. Through the successful synthesis of graphene- and MXene-based electrode materials derived entirely from CRM-free precursors, the consortium has demonstrated that high performance and environmental responsibility can be effectively combined. These materials were produced using green, non-toxic, and hazard-free processes, setting a new benchmark for sustainable electrode manufacturing in the energy storage sector.

Equally significant are the advances in ionic liquid electrolytes, which have resulted in thermally and chemically stable, non-flammable formulations. These next-generation electrolytes not only enhance device safety and longevity but also simplify supercapacitor design, reducing reliance on complex thermal management systems. This integrated approach exemplifies GREENCAP's commitment to technological excellence, circular design principles, and sustainable production practices.

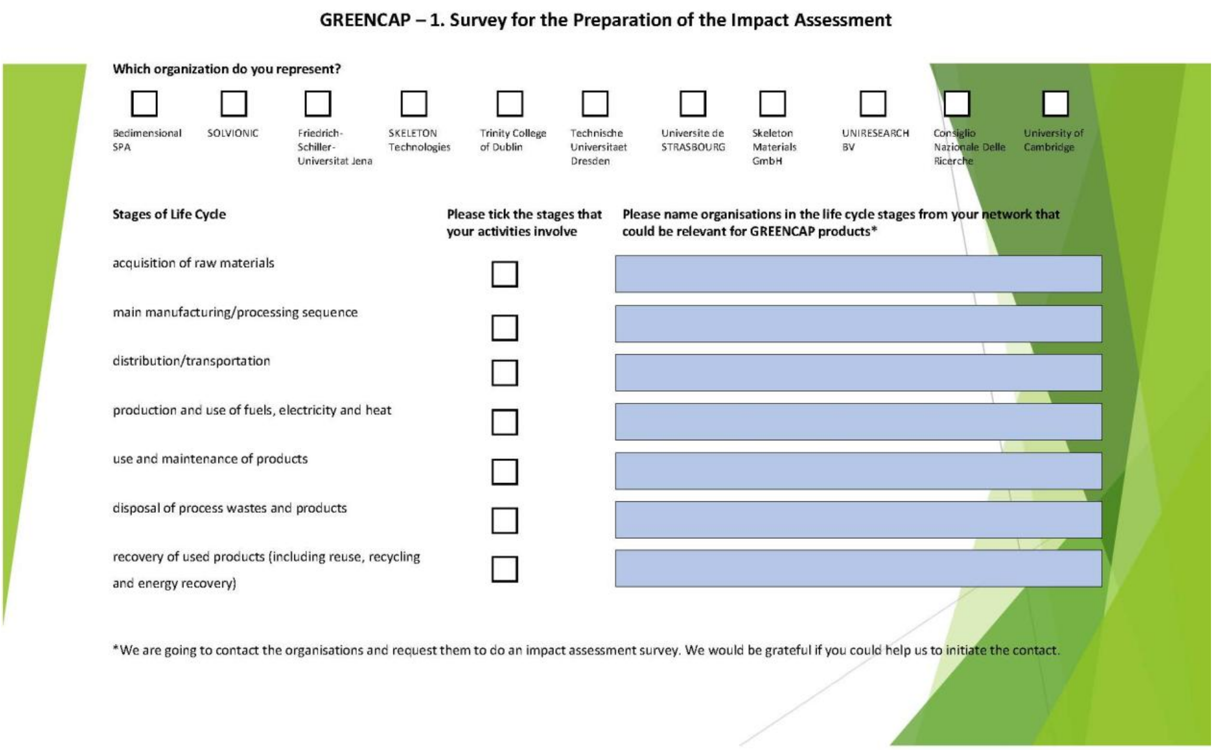
The ex-post assessment further underscores the project's strategic sourcing framework, prioritizing European raw materials to reinforce supply-chain resilience and minimize external dependencies. This approach is fully aligned with the EU's policy objectives on CRM substitution, strategic autonomy, and the Green Deal, thereby contributing directly to Europe's industrial competitiveness and sustainability leadership. GREENCAP's innovations in CRM reduction and replacement provide a solid scientific and technical foundation for the implementation of the EU Action Plan on Critical Raw Materials, making it a reference point for future policy and research initiatives.

Beyond technical innovation, GREENCAP has successfully built a vibrant and interdisciplinary ecosystem, integrating universities, R&D institutes, and industrial partners across multiple European countries. This collaborative framework has fostered knowledge transfer, capacity building, and stakeholder engagement, ensuring that the project's impact extends well beyond its immediate scientific outputs. The socio-economic analyses and targeted stakeholder surveys confirm both the strong market potential and the strategic relevance of GREENCAP technologies, while identifying pathways for scaling production, refining technical readiness, and enhancing life cycle performance through continuous R&D and iterative validation.

The comprehensive Life Cycle Assessment conducted using Ecoinvent 3.10 database provided robust, data-driven insights into the environmental advantages of GREENCAP's CRM-free SCs. The iterative testing of raw materials and the regular updating of environmental indicators ensured high analytical accuracy and transparency of results, reaffirming GREENCAP's scientific rigor and commitment to evidence-based sustainability.

In summary, GREENCAP stands as a European flagship initiative in the transition toward sustainable, high-performance, and CRM-independent energy storage technologies. The project not only delivers tangible scientific and technological breakthroughs but also lays the groundwork for future industrial deployment, policy alignment, and global competitiveness. Looking ahead, GREENCAP’s achievements provide a strategic springboard for further advancements in green materials science, scalable manufacturing, and integrated energy systems, ensuring that the consortium remains a driving force in shaping Europe’s sustainable energy future.

5 Appendix - Impact Assessment Questionnaire



GREENCAP – 1. Survey for the Preparation of the Impact Assessment

Which organization do you represent?

- ☐ Bedimensional SPA
- ☐ SOLVIONIC
- ☐ Friedrich-Schiller-Universitat Jena
- ☐ SKELETON Technologies
- ☐ Trinity College of Dublin
- ☐ Technische Universitaet Dresden
- ☐ Universite de STRASBOURG
- ☐ Skeleton Materials GmbH
- ☐ UNIRESEARCH BV
- ☐ Consiglio Nazionale Delle Ricerche
- ☐ University of Cambridge

Stages of Life Cycle	Please tick the stages that your activities involve	Please name organisations in the life cycle stages from your network that could be relevant for GREENCAP products*
acquisition of raw materials	☐	
main manufacturing/processing sequence	☐	
distribution/transportation	☐	
production and use of fuels, electricity and heat	☐	
use and maintenance of products	☐	
disposal of process wastes and products	☐	
recovery of used products (including reuse, recycling and energy recovery)	☐	

*We are going to contact the organisations and request them to do an impact assessment survey. We would be grateful if you could help us to initiate the contact.

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WP 5: Benchmarking & Impact Assessment

Survey of the critical raw materials used

Name of institution:

Please indicate whether CRMs are used in the work process of your activities in the GREENCAP project. If this is the case, please list the names of the CRMs and, if possible, please provide us with information about the source of the CRMs (company name etc.)

Are CRMs used	No	Yes, please list the name of CRMs used
Electrode (Including every electrode component, as well as the inactive materials)	☐	
Electrolyte	☐	
Separator	☐	
Casing	☐	
OEM (Original Equipment Manufacturer) **BCU** (Battery Control Unit) **BMU** (Battery Management Unit) **SMU** (Safety Management Unit) **ThMU** (Thermal Management Unit)	☐	

2023 Critical Raw Materials (*Strategic Raw Materials in italics*)			
aluminium/bauxite	coking coal	*lithium*	phosphorus
antimony	feldspar	*LREE*	scandium
arsenic	fluorspar	*magnesium*	*silicon metal*
baryte	*gallium*	*manganese*	strontium
beryllium	*germanium*	*natural graphite*	tantalum
bismuth	hafnium	niobium	*titanium metal*
boron/borate	helium	*PGM*	*tungsten*
cobalt	*HREE*	phosphate rock	vanadium
		*copper**	*nickel**

* Copper and nickel do not meet the CRM thresholds, but are included as Strategic Raw Materials.

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WP 5: Benchmarking & Impact Assessment

3. Survey of CRM-free materials used

Name of institution:

As our project is currently intensively engaged in the comparative analysis of different materials (incl. CRM and CRM-free), we have set up this third survey as a supplement to the 2nd one in order to create an overview of the CRM-free materials used. Please indicate which CRM-free materials are used in your activities in the GREENCAP project. Please list the names of the materials and, if possible, give us information about the source of the materials (company name, etc.).

Components	No	Yes, please list the name of materials used	Source of the materials
Electrode (Including anode/cathode active materials, as well as the inactive materials)			
Electrolyte			
Separator			
Casing			
OEM (Original Equipment Manufacturer) **BCU (**Battery Control Unit) **BMU** (Battery Management Unit) **SMU** (Safety Management Unit) **ThMU** (Thermal Management Unit)			

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4. Survey of raw materials used

Name of institution:

Please indicate all raw materials (including CRM and CRM-free materials) you use in your activities. When listing materials, kindly provide information about the source, such as company names and addresses, if possible.

Components	No	Yes, please list the name of materials used	Source of the materials
Electrode (Including anode/cathode active materials, as well as the inactive materials)	☐		
Electrolyte	☐		
Separator	☐		
Casing	☐		
OEM (Original Equipment Manufacturer) **BCU** (Battery Control Unit) **BMU** (Battery Management Unit) **SMU** (Safety Management Unit) **ThMU** (Thermal Management Unit)	☐		

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WP 5: Benchmarking & Impact Assessment

5. Survey of raw materials used

Name of institution:

Please update the **latest raw material names** in the table below. Please turn on the "**Track Changes**" setting in Word so that everyone can know the update status of the raw materials.

Components	**Critical Raw Materials (CRMs)**	**CRM-free materials**
Electrode (Including every electrode component, as well as the inactive materials)	Natural graphite, aluminum/bauxite, copper	Few-layer graphene, curved graphene, binder (CMC and SBR), Ti_3AlC_2/Mo_2Ga_2C, activated carbon, PTFE, $Ti_3C_2T_x$, Ti_2AlCTx, Ti_2CT_x, $Ti_3AlC_2T_x$, $Mo_2Ga_2CT_x$, Mo_2CT_x, Ti_3AlCNT_x, Ti_3CNT_x, $(Mo_2/3Y1/3)2AlC$, (Mo2/3Y1/3)2C, $CuCl_2$, NaCl, KCl, $CuBr_2$, NaBr, KBr
Electrolyte	Fluorspar	Acetonitrile, TEABF4, Pyr13FSI, N1113FSI, Pyr14BF4, Pyr1HTFO, N111HTFO, N111HTFSI, Gamma-valerolactone, Propylene carbonate
Separator		Cellulose, Glass Fiber, Celgard 3501
Casing	Aluminum/bauxite	Stainless steel coin cell parts, polypropylene gasket, spring
OEM (Original Equipment Manufacturer) **BCU** (Battery Control Unit) **BMU** (Battery Management Unit) **SMU** (Safety Management Unit) **ThMU** (Thermal Management Unit)	Aluminum/bauxite	Plastic components, cables

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WP 5: Benchmarking & Impact Assessment

1. Survey of the socio-economic impact

Name of institution:

Based on our benchmarking activities, the D60 form has been selected in the GREENCAP project. Therefore, all subsequent references to supercapacitors, supercapacitor modules, and supercapacitor systems in the following questions will pertain to the D60 form.

Q1: Which sectors are the primary customers of your company's supercapacitors?

Type / Options	Supercapacitors	Supercapacitor modules	Supercapacitor systems
A. Public transportation (buses, trams, subway, trains, ships, aircraft) B. Heavy transportation C. Cars D. Smart grids (Solar energy, wind energy, hydro energy) E. Industrial machinery F. Other (please specify)	☐ A ☐ B ☐ C ☐ D ☐ E ☐ F	☐ A ☐ B ☐ C ☐ D ☐ E ☐ F	☐ A ☐ B ☐ C ☐ D ☐ E ☐ F

Q2: What is the average annual sales volume range?

Type / Options	Supercapacitors (item)	Supercapacitor modules (item)	Supercapacitor systems (item)
A. 1 – 10 B. 10 – 100 C. 100 – 500 D. 500 – 1,000 E. Other (please specify)	☐ A ☐ B ☐ C ☐ D ☐ E	☐ A ☐ B ☐ C ☐ D ☐ E	☐ A ☐ B ☐ C ☐ D ☐ E

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Q3: Could you provide a price range for different products' costs and profit margins?

Options \ Type	Supercapacitors (€/kWh)	Supercapacitor modules (€/kWh)	Supercapacitor systems (€/kWh)
A. Cost: < 5,000, profit: < 2,000 B. Cost: 5,000 – 10,000, profit: 2,000 – 5,000 C. Cost: 10,000 – 15,000, profit: 5,000 – 7,500 D. Cost: > 15,000, profit: > 7,500 E. Other (please specify)	☐ A ☐ B ☐ C ☐ D ☐ E ____	☐ A ☐ B ☐ C ☐ D ☐ E ____	☐ A ☐ B ☐ C ☐ D ☐ E ____

Q4: How would you rate the overall cost-effectiveness of supercapacitors compared to other energy storage solutions?

☐ A. Much more cost-effective
☐ B. More cost-effective
☐ C. Equally cost-effective
☐ D. Less cost-effective
☐ E. Much less cost-effective

Q5: Have purchasers provided feedback regarding their satisfaction with the use of supercapacitors? If so, what are the primary strengths and weaknesses they have identified?

☐ (1) Yes, feedback has been received:

Strengths:

☐ A. High energy efficiency
☐ B. Fast charging/discharging capability
☐ C. Long lifespan/durability
☐ D. Low maintenance requirements
☐ E. Other (please specify) ____

Weaknesses:

☐ A. Limited energy storage capacity
☐ B. Higher upfront costs
☐ C. Bulkiness/size concerns
☐ D.Performance variability in different environments
☐ E. Other (please specify) ____

☐ (2) No, feedback has not been received
☐ (3) Not sure

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Q6: In what ways could the development of supercapacitors enhance the performance of existing supercapacitors? Additionally, in which areas could these improvements lead to new growth opportunities?

(1) Potential Improvements:

- ☐ A. Increased energy storage capacity
- ☐ B. Faster charge/discharge cycles
- ☐ C. Enhanced durability and lifespan
- ☐ D. Reduced size and weight
- ☐ E. Improved cost-effectiveness
- ☐ F. Other (please specify) ____________________

(2) Growth Opportunities:

- ☐ A. Expanding into new markets (e.g., electric vehicles, renewable energy storage)
- ☐ B. Enabling new applications (e.g., wearable electronics, grid stabilization)
- ☐ C. Strengthening competitive positioning in existing markets
- ☐ D. Supporting the development of more sustainable/eco-friendly products
- ☐ E. Other (please specify) ____________________

Q7: How do you foresee the demand for supercapacitors evolving in the next 5 years?

- ☐ A. Significant increase
- ☐ B. Moderate increase
- ☐ C. No significant change
- ☐ D. Moderate decrease
- ☐ E. Significant decrease
- ☐ F. Not sure

Q8: What challenges does your company face in integrating supercapacitors into existing systems or products?

- ☐ A. Compatibility with existing infrastructure
- ☐ B. High initial investment costs
- ☐ C. Limited technical expertise
- ☐ D. Supply chain constraints
- ☐ E. Regulatory hurdles
- ☐ F. Other (please specify) ____________________

Q9: Which external factors could significantly impact the adoption and deployment of supercapacitors in industry?

- ☐ A. Technological advancements
- ☐ B. Government regulations and policies
- ☐ C. Changes in energy prices
- ☐ D. Shifts in consumer preferences
- ☐ E. Competitive pressures
- ☐ F. Other (please specify) ____________________

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Supercapacitor Socio-Economic Impact Assessment Survey

Name of Institution: ______________________

KPI	Parameter	Unit	Global State-of-the-art	Skeleton Benchmarking	GREENCAP Prototype
1	Energy density	Wh/L	10.60	10.90	13.40
2	ESR 1s	mOhm	0.23	0.21	0.258
3	Cycle life	Cycles	1,000,000	1,000,000	350,000
4	Capacitance	F	3,400	3,400	4,500
5	Rated voltage	V	3.0	3.0	2.85

Table 1. Performance and Price of Supercapacitor Products

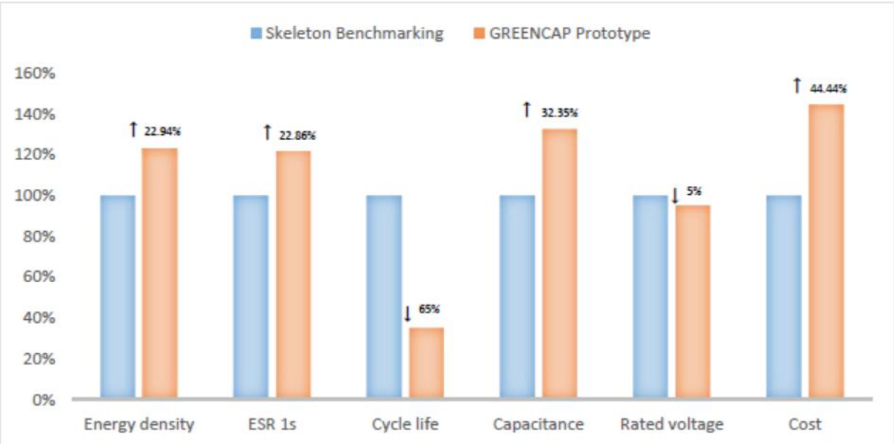

Figure 1. A Comparison between Benchmarking and the GREENCAP Prototype

In light of the above data, which aspects require further improvement?

- ☐ Higher energy density
- ☐ Longer cycle life
- ☐ Faster charging speed
- ☐ Larger Capacitance
- ☐ Lower cost
- ☐ Other (please specify): ______________________

The diagram above illustrates a relative comparison of the performance and price of the GREENCAP product against the benchmark model from Skeleton Technologies. For reference, the Skeleton benchmark values are normalized to 100% and serve as the baseline.

Following our benchmarking activities, the D60 form has been selected for use in the GREENCAP project. Accordingly, all subsequent references to supercapacitors in this survey will specifically concern the Skeleton Technologies D60 form.

We sincerely appreciate your participation. The GREENCAP project aims to evaluate the societal, economic, and technological impacts of supercapacitors. Your responses will provide essential insights into current perceptions and will help inform future developments in this field.

Disclaimer: when selecting multiple choices in the survey, please be informed that in general, improvements in one aspect of energy storage devices may affect other aspects negatively, due to the storage nature and cell limitations.

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Project partners:

#	Partner short name	Partner Full Name
1	BED	BEDIMENSIONAL SPA
2	SOLV	SOLVIONIC
3	FSU	FRIEDRICH-SCHILLER-UNIVERSITAT JENA
4	SKL	SKELETON TECHNOLOGIES OU
5	TCD	THE PROVOST, FELLOWS, FOUNDATION SCHOLARS & THE OTHER MEMBERS OF BOARD, OF THE COLLEGE OF THE HOLY & UNDIVIDED TRINITY OF QUEEN ELIZABETH NEAR DUBLIN
6	TUD	TECHNISCHE UNIVERSITAET DRESDEN
7	UNISTRA	UNIVERSITE DE STRASBOURG
8	SM	SKELETON MATERIALS GMBH
9	UNR	UNIRESEARCH BV
10	CNR	CONSIGLIO NAZIONALE DELLE RICERCHE
11	UCAM	THE CHANCELLOR MASTERS AND SCHOLARS OF THE UNIVERSITY OF CAMBRIDGE
12	CU	Y CARBON LLC

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