HORIZON EUROPE PROGRAMME

TOPIC HORIZON-CL4-2022-RESILIENCE-01-24

GA No. 101091572

Graphene, MXene and ionic liquid-based sustainable supercapacitor

GREENCAP - Deliverable report

D5.1. Ex-ante Environmental and Socio-economic Impact Assessment

Funded by
the European Union

Deliverable No.	GREENCAP D5.1	
Related WP	WP5	
Deliverable Title	Ex-ante Environmental and Socio-economic Impact Assessment	
Deliverable Date	2023-09-30	
Deliverable Type	REPORT	
Dissemination level	Public (PU)	
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Approved by	Francesco Bonaccorso (BED) – Project coordinator	2023-09-26
Status	Final	2023-09-26

Document History

Version	Date	Editing done by	Remarks
V01	2023-09-06	TUD	First draft
V02	2023-09-23	TUD	Second draft
V03	2023-09-25	TUD	Third draft
V1.0	2023-09-15	UNR	Review
V2.0	2023-09-19	BED	Review
V3.0	2023-09-25	BED	Review

Summary

This report presents the ex-ante environmental and socio-economic impact assessment, serving as the inaugural deliverable (D5.1) under WP5: Benchmarking & Impact Assessment. It consolidates the findings from impact assessment activities executed by Task 5.2 (Environmental impact assessment) and Task 5.3 (Socio-economic impact assessment) over the initial six months of the project.

Conforming to the Horizon Europe Data Management Plan template, the deliverable is divided into four main sections. The initial section provides context for the ex-ante impact assessment. The subsequent section delves into the environmental repercussions of GREENCAP supercapacitors, centralizing on a cradle-to-gate life cycle analysis. The third section examines the socio-economic ramifications, particularly highlighting the engagement with critical raw materials (CRMs) and CRM-free methodologies in the advancement of GREENCAP's supercapacitors. The final segment offers conclusions and creates a segue into the forthcoming ex-post impact assessment.

Data that informed this ex-ante assessment was primarily sourced from:

- *Three comprehensive questionnaires that provided information on critical and non-critical raw materials used within the GREENCAP project.*
- *Informal expert dialogues with members from various consortium institutions, offering perspectives on projected trajectories in mitigating and sidestepping the usage of CRMs.*
- *Technical insights garnered from project meetings, which underpinned further documentary research to extract cutting-edge progress in both theoretical and applied spheres regarding the deployment of CRMs in supercapacitor technology.*

The ex-ante assessment shows that a significant portion of GREENCAP's raw materials is predominantly European-sourced, reducing reliance on non-European Union (EU) nations and bolstering resilience against potential supply disruptions. Notably, the GREENCAP project has achieved commendable progress in pioneering CRM-free supercapacitors. Graphene and MXene-based electrode materials have been successfully produced from CRM-free precursors and using environmentally friendly approaches, eliminating the use of toxic/hazardous chemicals. Innovations in the synthesis of ionic liquids permitted the formulation of novel thermally/chemically stable and non-flammable-based electrolytes. Such achievements underscore the consortium's dedicated efforts in identifying viable alternatives to CRMs. This assessment stands as a critical knowledge reservoir for stakeholders navigating the EU's action plan on CRMs.

Honoring a “develop by doing” ethos, this ex-ante analysis served as both a testbed and a refinement tool for our impact assessment framework conceived early in the project. The insights and experience gained have paved a robust foundation for the subsequent ex-post impact assessment phase.

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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-ante impact assessment

GREENCAP aims to unlock the full potential of supercapacitors (SCs) as electrochemical energy storage systems, supporting the transition towards the climate-neutrality set by the European Union (EU)'s international commitments under the Paris Agreement, while ensuring the targets of EU's Action Plan on Critical Raw Materials (CRMs). GREENCAP is developing a CRM-free SC technology exhibiting a battery-like energy density (>20 Wh/kg, >16 Wh/L), together with the distinctive superior power densities and high cycle life of traditional electrochemical double layer capacitors, by exploiting layered two-dimensional materials (2DMs), including graphene and MXenes, as electrode materials, and ionic liquids (ILs) as high-voltage electrolytes.

In line with Europe's ambition concerning the Green Deal, it is fundamental to accompany material research in the GREENCAP project with a comprehensive environmental, societal, and economic impact assessment. The environmental impact assessment of GREENCAP technology focuses on the entire life cycle (raw material acquisition, product production, and waste management) of the raw materials used in the project, and the socio-economic impact assessment focuses on the societal-economic impact, technological and scientific impacts, so that a promising business case can be identified to achieve a successful exploitation strategy for establishing a new industrial value chain with the newly developed SCs.

Ex-ante impact assessment provides a comprehensive and coherent analysis of the foreseeable impacts associated with project implementation. As GREENCAP works to develop CRM-free SCs, this assessment plays a key role not only in providing insight into the project's potential outcomes, but also in guiding its strategic decisions. By conducting this assessment, GREENCAP aims to facilitate informed decision-making by a wide range of stakeholders, including researchers, industry partners, policymakers, and the wider community.

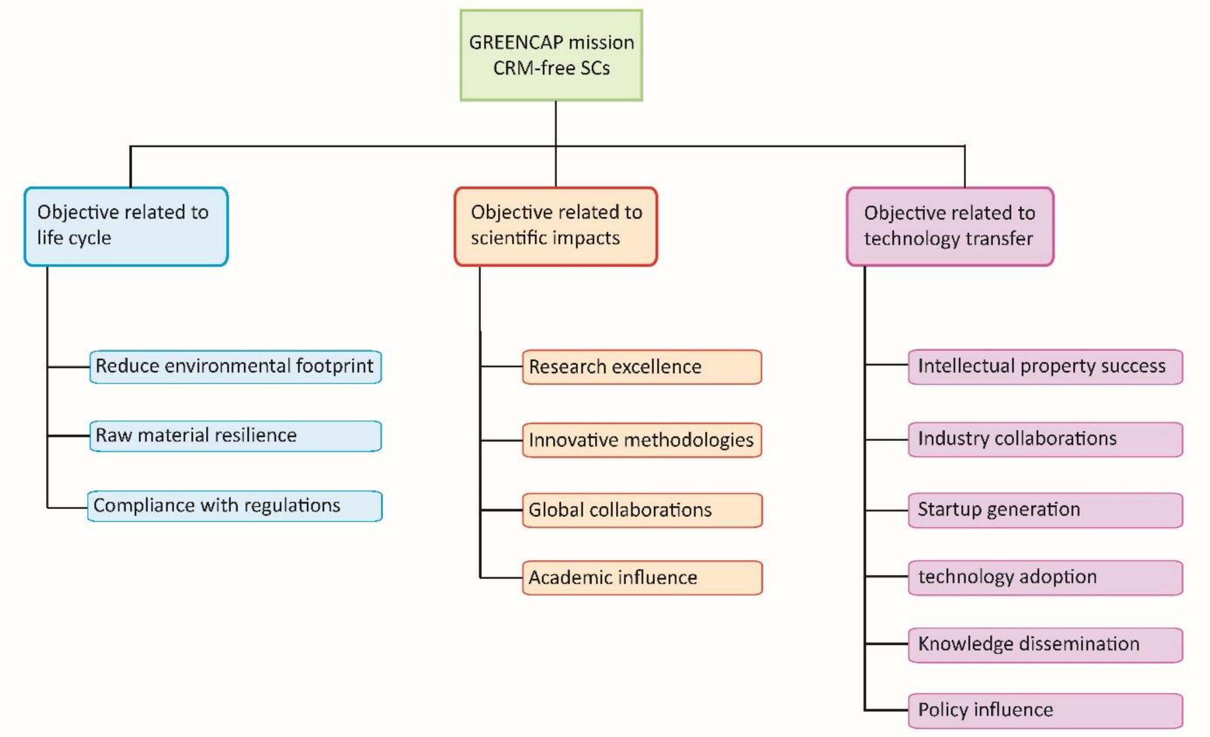
1.2 Impact assessment framework

Our impact assessment employs the Objectives and Key Results (OKR) methodology. OKRs constitute a highly dynamic and interactive methodology that is seamlessly coordinated with the GREENCAP mission: Develop a CRM-free technology for supercapacitors that exhibits battery-like energy density, as well as superior power density and high cycle life unique to traditional electrochemical double-layer capacitors.

The OKR methodology has emerged as a vital tool for evaluating our progress in attaining these objectives. It embodies a versatile approach that encourages experimentation and the exploration of diverse solutions to propel us closer to each goal. This approach not only sustains our unwavering commitment to our objectives but also nurtures a culture of high-performance within the GREENCAP project.

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

Figure 1. *Impact assessment framework.*



(1) Life Cycle: The primary objectives within the life cycle dimension revolve around the achievement of an environmentally friendly supercapacitor life cycle. The overarching goal is to minimize the environmental impact encompassing the entire spectrum, from the extraction of raw materials through manufacturing, utilization, and eventual disposal. These objectives are intricately aligned with broader sustainability principles. Key results within this dimension are assessed from three critical vantage points:

- *Reduction of environmental footprint.*
- *Enhancement of raw material resilience.*
- *Adherence to regulatory compliance.*

(2) Scientific Impact: Within this dimension, the foremost aim is to propel the boundaries of scientific knowledge. Key results in this realm are meticulously examined with a focus on:

- *Attainment of research excellence.*
- *Pioneering innovative methodologies.*
- *Cultivation of global collaborations.*
- *Influence on academic spheres.*

(3) Technology Transfer: This dimension is dedicated to the facilitation of seamless technological transitions. The central objective is to foster the effective transfer of developed technologies. Key results in this dimension are scrutinized based on:

- *Success in intellectual property endeavors.*
- *Forging strategic partnerships with industry stakeholders.*

- *Incubation of startups.*
- *Adoption and adaptation of technologies by industries, governments, or entities.*
- *Knowledge dissemination through training sessions and workshops.*
- *Influencing policy decisions.*

2 Environmental impact assessment

2.1 Goal and scope

2.1.1 Background and objectives

Supercapacitors are promising electrochemical energy storage systems that can drastically reduce or even eliminate the use of CRMs (*e.g.*, Li, Co, and natural graphite) compared to current market-dominating technologies, including Li-ion batteries (LiBs). GREENCAP is exploiting layered 2DMs, including graphene and MXenes, as electrode materials, and ILs as high-voltage electrolytes. The *ad hoc* choice of graphene, MXene and ILs can lead to advanced high-energy density SCs with performance surpassing the state-of-the-art SCs, reaching LiB-like energy densities.

Key objectives of this environmental impact assessment are:

- *Providing knowledge of GREENCAP's environmental advantages and disadvantages.*
- *Demonstrating the robustness of GREENCAP outcomes through meticulous sensitivity analysis.*
- *Providing GREENCAP with quantitative data for the selection of raw materials and the adjustment of production processes.*

Our impact assessment methodology strictly aligns with the International Standards on Life Circle Assessment, notably ISO 14040: Environmental management – Life cycle assessment – Principles and framework, and ISO 14044: Environmental management – Life cycle assessment – Requirements and guidelines.

2.1.2 Functional unit

The cornerstone for our impact assessment is anchored at a 1 kWh SC stack.

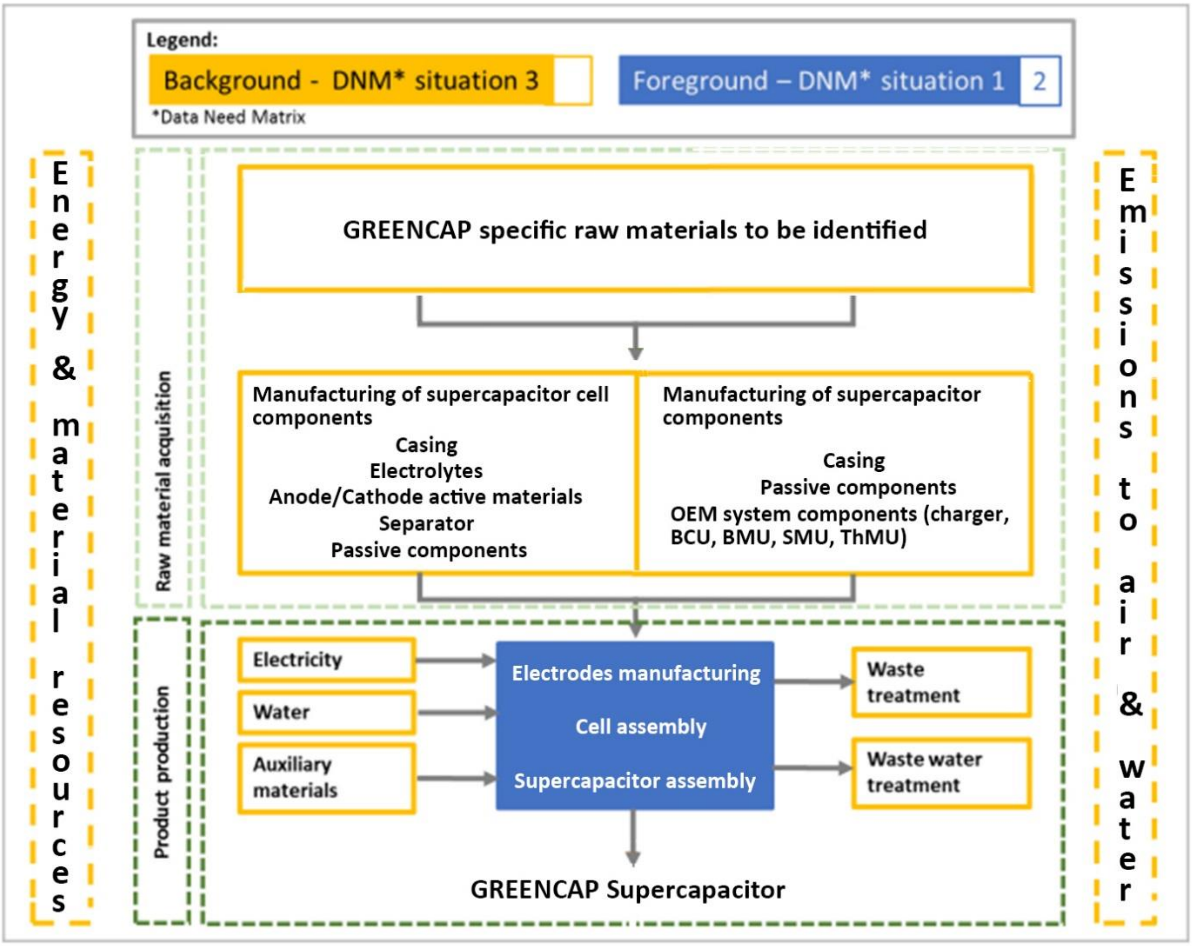
2.1.3 System boundaries

Our design adopts a "cradle-to-gate" stance for the life cycle assessment, encompassing raw materials procurement to product formation, depicted in Figure 2.

Our environmental impact assessment delineated these critical SC developmental phases:

- *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 GREENCAP production.*



(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, but we have access to specific information.*
- *Situation 3: 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 holistic environmental assessment rooted in life cycle philosophies pivots on exhaustive itemization and quantification of flows enveloping the system. The mapped flows encapsulate:

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

- *emissions to the ground.*

The inventory of these flows for the given system is divided into two 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 and use of a 1 kWh SC stack.*

Upon summarizing these flows, the GREENCAP SCs are analysed through the study of environmental impact indicators.

2.2.2 Environmental impact indicators

Our ex-ante environmental footprint impact assessment has been meticulously executed to dissect and elucidate the prospective environmental impacts inherent within the product life cycles, specifically for SCs. For this rigorous assessment, we've incorporated well-defined environmental impact categories, centring our analysis around the midpoint category. This choice allows us to focus on primary environmental impacts that bridge the gap between emissions and the ensuing potential detrimental effects.

In selecting impact categories, we've adhered strictly to established Life Cycle Assessment (LCA) protocols and have chosen models that offer precision, ensuring there is minimal uncertainty regarding the data's characteristics, completeness, and availability. It's worth highlighting that our criteria are firmly rooted in the ISO 14040 and ISO 14044 standards. Although we've endeavored to be as comprehensive as possible, capturing the entirety of environmental nuances remains challenging. The depth and breadth of our assessment were, in part, contingent upon the caliber of available inventory datasets.

To enhance clarity, we've adopted the ISO 14044's standardized terminology for our inventory categories and their indicators. The impact categories specifically reflect the environmental concerns we've chosen to spotlight. These concerns are directly tied to the Life Cycle Inventory (LCI) analysis results, categorized for each functional unit. The cumulative outcomes are articulated *via* category indicators, each capturing the prospective environmental ramifications tied to individual functional units, as elaborated in Table 1.

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

Impact category	Indicator	Unit
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

To analyze the LCI of the SCs, we initiated a questionnaire survey at the outset of the GREENCAP project (see Appendix). This survey aimed to identify relevant organizations within the GREENCAP project consortium for impact assessment surveys. The results from Survey 1 are presented in Table 2.

***Table 2.** Organizations relevant for GREENCAP products.*

Stages of Life Cycle	Organisations that could be relevant for GREENCAP products
Acquisition of raw materials	Sigma Aldrich, AMG Graphite GK, Georg H. Luh GmbH, Imerys Graphite & Carbon Switzerland SA, Asbury Carbons Inc, Solvionic, Synthetic graphite from Imerys, Carbon Ukraine, Jilin 11 Technology Co.,Ltd , SGL Carbon
Main manufacturing/processing sequence	SKELETON Technologies, VARTA AG, Fisher Scientific, C-Tech Innovation, Gamesa Electric

Stages of Life Cycle	Organisations that could be relevant for GREENCAP products
Distribution/transportation	Mail Boxes Etc., DHL
Production and use of fuels, electricity and heat	Enel, Gas- Corona Energy, Electricity- EDF Energy, C-Tech Innovation, Gamesa Electric, AGSM AIM Energia Spa
Use and maintenance of products	ENI S.p.A., EnelX S.r.l., Thales Research & Technologies, Duferco Engineering, SIEMENS GAMESA RENEWABLE ENERGY
Disposal of process waste and products	Biffa, Recurfix Srl
Recovery of used products (including reuse, recycling, and energy recovery)	Biffa, Münster University, Avesta Battery & Energy Engineering B.V.B.A.

As depicted in Figure 3, the organizations associated with the GREENCAP project are predominantly located in Europe. Only a few are based in Asia and the Americas. This distribution indicates that the products investigated in the GREENCAP project have minimal dependence on countries outside of Europe.

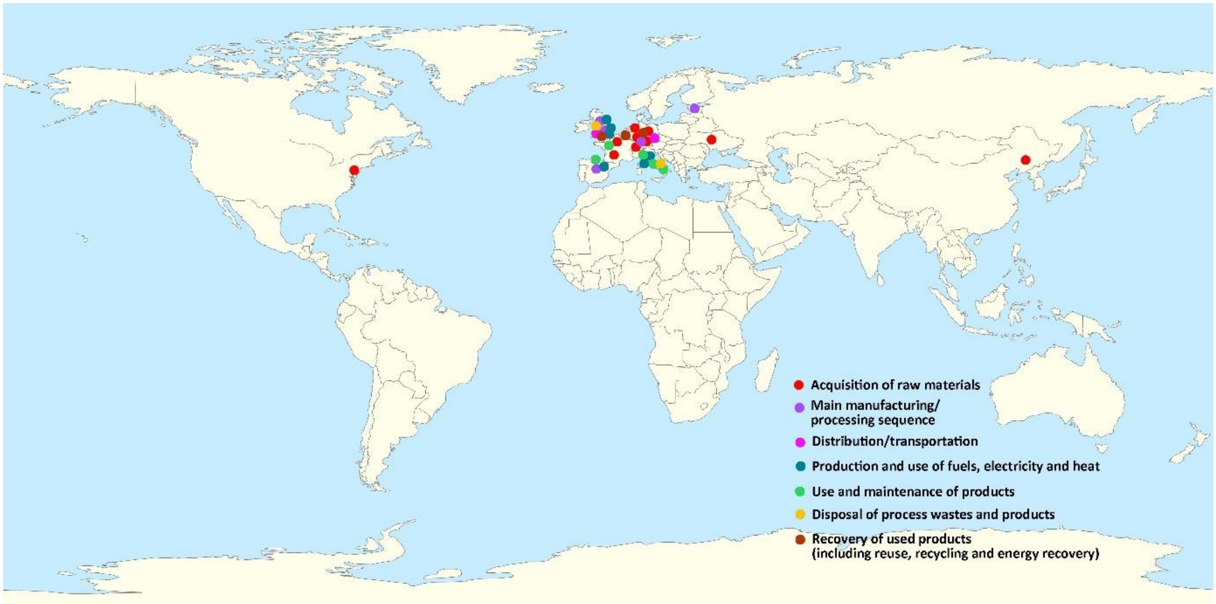


Figure 3. *Location for organisations that are relevant for GREENCAP products.*

2.3.1 Raw material acquisition

The results of two surveys undertaken up until June 2023 reveal the raw materials used in the GREENCAP project. Our analysis of these materials is divided into two categories: CRMs and CRM-free materials. The primary components encompassed by this categorization include electrodes, electrolyte, separator, casing, and Original Equipment Manufacturer.

As per the current stage of the project, the CRMs incorporated are natural graphite, aluminum/bauxite, fluorspar, and copper, detailed further in Table 3. Given the strategic direction of the project, forthcoming activities will actively explore alternative materials, aiming to either replace or diminish the consumption of these four CRMs.

Table 3. *Raw materials used in GREENCAP (up until June 2023)*

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, $CuCl_2$/$CuBr_2$/NaCl/KCl
Electrolyte	Fluorspar	Acetonitrile
Separator		Cellulose Glass Fiber type A
Casing	Aluminum/bauxite	Stainless steel coin cell parts, polypropylene gasket
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

* 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]

2.3.2 Product production

The production of SCs encompasses various stages such as electrode manufacturing, cell assembly, and SCs assembly. As of now, the GREENCAP project is still in its preliminary phases and has not yet advanced to the research stage specific to SC production.

3 Socio-economic impact assessment

3.1 Goal and Scope

3.1.1 Background and objectives

Critical raw materials hold strategic significance for the EU's economy and its various industrial sectors due to their pronounced supply risks and substantial economic importance. These materials are indispensable across numerous industries and technologies, underpinning the EU's competitive edge and sustainability. CRMs are pivotal for European economic progression, technological advancement, and the realization of environmental sustainability goals. The EU has long recognized the importance of these materials. As early as 2011, the EU began establishing initiatives such as the Critical Raw Materials Action Plan to confront challenges tied to the supply and responsible sourcing of CRMs. Recognizing the evolving nature of material significance and supply risks, the EU continues to update the CRM list regularly, ensuring it remains reflective of the current geopolitical, economic, and technological landscape. This dynamic process demonstrates the EU's commitment to staying ahead of challenges and adapting to the ever-changing global materials market.

The GREENCAP project's endeavour to produce CRM-free SCs aims at fostering raw material resilience. By phasing out reliance on CRMs — which are susceptible to supply risks and price volatility — these SCs should ensure reduced dependency, boosting resilience against supply chain disruptions. This development complements sustainability goals and circular economy principles. Thus, this socio-economic impact assessment evaluates the implications of GREENCAP SCs with an emphasis on raw material resilience, mapping their contribution to the EU's social and economic fabric.

3.1.2 Assessment scope and indicators

We conducted a comprehensive ex-ante socio-economic impact assessment to deeply explore and elucidate the socio-economic effects of GREENCAP products. This meticulous assessment encompassed well-defined categories, distinctly divided into two primary areas: scientific impacts and impacts on technology transfer. This distinction is especially relevant to the development of CRM-free SCs, a domain where GREENCAP has pioneered (as detailed in Table 4). The assessment places significant emphasis on evaluating the resilience of raw materials used in SC production and their pivotal role in advancing the social and economic sustainability of the EU.

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 4. *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

Regarding electrode materials, the GREENCAP project team is looking for alternatives to CRMs. Graphene and MXene-based electrode materials have been successfully produced from CRM-free precursors and using environmentally friendly approaches, eliminating the use of toxic/hazardous chemicals. Recent research into sustainable electrolytes has yielded significant achievements, including the successful synthesis of ILs for high-voltage electrolytes, such as $Pyr_{13}FSI$, $N_{1113}FSI$, $Pyr_{14}BF_4$, 1M $Pyr_{14}BF_4$ in ACN, 1M $N_{1113}FSI$ in ACN, EMIFSI, N111HTFO-Trimethylammonium triflate (hydrophilic), N111HTFSI-Trimethylammonium bis (trifluoromethanesulfonyl) imide (hydrophobic), Pyr1HTFO-N-methylpyrrolidinium triflate (hydrophilic).

3.2.3 Scientific outputs and impacts

(1) Innovative SC management systems (SMSs)

GREENCAP's SC technology, with its novel SoX monitoring tools and SMS, is trying to eliminate the need for sophisticated management systems, instead required for batteries, enabling greater safety and less maintenance (fit-and-forget approach). In SCs, the elimination of sophisticated thermal and energy management systems is associated with their low risk of parasitic side reactions and the low heat evolution during charging and discharging. By monitoring SC SoX and preventing reverse polarity, the refining of traditional SMSs for electrochemical double layer capacitors (EDLCs) maximizes the GREENCAP’s SC performances (energy and power density), while guaranteeing long cycle life (>10^6 cycles).

(2) Publications and conferences

While GREENCAP is fundamentally rooted in materials innovation, the initial eight months have witnessed a surge in intensive materials research, marking a productive phase. The socio-economic impact during this period is developing steadily. Throughout the initial eight months of the ex-ante impact assessment phase, the GREENCAP project's activities, including publications and participation in conferences, showed promising progress, increasing after the initial first six months. It's important to note that this aligns with the usual trajectory for such projects, as they tend to gain significant momentum in the later phases as more results are produced. In fact, GREENCAP's project partners are actively contributing to this progress, based on our monthly project meetings and statistics on publications and participation in circle meetings and conference attendance.

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

The GREENCAP project serves as a successful example of uniting researchers from diverse countries and organizations. This collaborative culture within GREENCAP offers a multitude of advantages, prominently including the pooling of resources, the prevention of duplicative efforts, and the facilitation of coordinated actions. By bringing together experts from various backgrounds and regions, GREENCAP not only advances its own goals but also contributes to the broader objectives of European excellence and capacity building. GREENCAP’s activities play a pivotal role in aligning with and advancing broader EU policy objectives. By fostering collaboration on a global scale, such initiatives yield substantial economic and social benefits and impacts. GREENCAP's commitment to cooperation and its contributions to these overarching policy objectives highlight the project's dedication to achieving greater excellence and promoting positive socio-economic outcomes within the EU.

3.3 Impacts on technology transfer

3.3.1 Technology transfer inputs

Key drivers for technology transfer within this project can be primarily categorized into monetary contributions and the dedicated staff at the facility. Technology transfer inputs are the same as scientific inputs.

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 15 news/events updates.*
- *As of July 2023: 198 website views and 87 unique visitors.*
- *A growing LinkedIn presence with 99 followers.*

Figures 4 offers visual data related to these platforms.

Figure 4. *Press and media activities. [2] [3]*

Visitors and followers of the GREENCAP progress are from the academic field, followed by Strategic Management Services, Appliances, Electrical, and Electronics Manufacturing, Electrical Equipment Manufacturing, and Chemical Manufacturing, showing that the main targets groups are engaged from the start of the project. Moreover, LinkedIn and website statistics report that the GREENCAP progress is followed by interested groups from all EU countries, with a significant presence also of audience in the United States (this information will also be revised and aligned regularly in close collaboration with the dissemination, communication and exploitation activities updates).

3.3.3 Technology transfer outputs and impacts

Drawing from the questionnaire analysis presented in Section 2, it becomes evident that the GREENCAP project places a strong emphasis on the sourcing of raw materials within the boundaries of

Europe. This strategic approach not only aligns seamlessly with the core initiatives of GREENCAP but also resonates with the broader goals set by the EU to enhance resource efficiency. By strategically focusing on local sourcing, GREENCAP achieves multiple critical objectives.

First and foremost, this approach ensures a reliable and secure supply of raw materials, a fundamental pillar in the foundation of any successful project. Moreover, it contributes significantly to the EU's sustainability aspirations. GREENCAP's commitment to sourcing locally minimizes the carbon footprint associated with material transportation and reinforces the principles of environmental responsibility. Furthermore, this localized sourcing strategy bolsters economic resilience within the EU. By supporting local industries and businesses involved in the extraction, production, and distribution of raw materials, GREENCAP actively participates in the growth and stability of the European economy.

In essence, GREENCAP's endeavors exemplify a commitment to technology transfer practices that harmonize with sustainable and resilient supply chain principles. By doing so, the project is playing a vital role in advancing the EU's objectives of fostering a green and sustainable economy.

4 Conclusion and Outlook

In summary, the GREENCAP project has showcased steady progress in the development of CRM-free SCs. Graphene and MXene-based electrode materials have been successfully produced from CRM-free precursors and using environmentally friendly approaches, eliminating the use of toxic/hazardous chemicals. Innovations in the synthesis of ionic liquids permitted the formulation of novel thermally/chemically stable and non-flammable-based electrolytes. Such a breakthrough not only paves the way for simplifying SC designs by obviating the need for intricate cooling systems but also resonates with sustainable and eco-friendly solvent practices.

The ex-ante assessment accentuates the consortium's strategic sourcing approach, emphasizing a significant inclination towards European raw materials. This not only diminishes the project's dependency on non-EU nations but also enhances its resilience against potential supply-chain disruptions. With innovations that promote alternatives to CRMs, the GREENCAP project exemplifies a robust commitment to a sustainable future. Such advancements also enrich the knowledge pool for stakeholders actively participating in the EU's action plan on CRMs.

While GREENCAP is fundamentally rooted in materials innovation, the initial eight months have witnessed a surge in intensive materials research, marking a productive phase, while the socio-economic impact during this period has been developing steadily. As the Impact Assessment Team, equipped with a blend of social science and engineering expertise, we remain cognizant of this trajectory. To further amplify our reach and share our experiences, we, as an impact assessment group, have sought a platform to engage with the broader impact assessment community, specifically targeting discussions on decarbonizing the energy sector at the globally renowned platform of 43rd Annual Conference of the International Association for Impact Assessment in April 2024. This will be a valuable complement to the series of conferences and other dissemination activities related to materials and supercapacitor technology in which the other scientific groups of the GREENCAP project are planning to participate.

Embracing a philosophy of “develop by doing”, this early analysis not only helped us get an initial sense of things but also allowed us to improve our impact assessment framework, which was designed at the start of the project. The invaluable insights and experiences gathered will undoubtedly lay a solid groundwork for the forthcoming ex-post impact assessment phase.

In the ex-post impact assessment phase, we intend to carry out an LCA of the GREENCAP SCs. For this analysis, we will utilize the *Umberto* software and the *Ecoinvent* database, aligning with the approach taken by the Task 5.1 benchmarking workgroup. This ensures synergistic collaboration between the different teams. Moreover, the raw materials earmarked for the SCs are currently in an extensive and dynamic testing phase, a procedure that underpins our sustainability commitments. Recognizing the fluid nature of these materials, we will administer questionnaires focused on the raw materials every 3 months. This iterative approach will ensure we consistently capture the most current and relevant data. Our environmental impact indicators will be recalibrated based on the specific raw materials and production processes deployed for the SCs.

For the socio-economic impact assessment, our strategy will be threefold:

- *We will conduct expert interviews to gather specialized insights.*

- *A randomized questionnaire survey will be administered to collect a broader set of data.*
- *Database surveys will serve as a foundational data source to enhance our understanding.*

Simultaneously, our evaluation of socio-economic impact will harness the OKR methodology. This robust framework has been fine-tuned to align seamlessly with our project's unique goals and objectives.

5 Risk and Deviations from Annex 1

No risks have arisen related to this deliverable. There are no deviations from the description of this deliverable as given in Annex I of the Grant Agreement.

6 References

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

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

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

7 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.

GA No. 101091572

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)			

8 Acknowledgement

The author(s) would like to thank the partners in the project for their valuable comments on previous drafts and for performing the review.

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

Disclaimer/ Acknowledgment

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101091572. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.