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InComEss

Innovative polymer-based composite systems
for high-efficient energy scavenging and storage

Deliverable

D1.2 Key Performance Indicators

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DISCLAIMER

EXECUTIVE SUMMARY / ABSTRACT

SCOPE

This report describes the different Key Performance Indicators (KPI) that will be used for the evaluation of materials and systems and for benchmarking along the project. The state-of-the-art values of equal or similar materials and systems are considered and goals describing a successful parameter are defined accordingly. Through the definition of these parameters, the success criteria at each step of the project can be used to evaluate the success of the project, referring to the expected results.

Each KPI will help describe and define how the end products are characterized and will serve as a guideline for all steps along the process of the project. The KPIs are further divided into the work packages which are going to be processed in a chronological manner along the project and describe both the individual components as well as the energy harvesting systems as a whole. The main focus of this deliverable is to create an overview as to the current performance parameter of the individual energy harvesting components (piezoelectric composite fibres, thermoelectric composites and supercapacitors) and the processes and scenarios that in the end define the goal performance and constraints of the energy harvesting systems.

Based on the raw materials and manufacturing processes of the different elements within the project (piezoelectric composite fibres, thermoelectric composite materials and supercapacitors) baselines to perform a comparison between current existing products and InComEss' innovations under a life cycle analysis (LCA) were set by CIRCE, which sets an observation to the materials that influence the development of the InComEss elements. Apart from the LCA baseline, the availability for baseline raw materials considering geological/geopolitical stability was also considered by means of Hubbert peak and expected demands.

LIST OF ACRONYMS

CRM	*Critical Raw Materials*
EHS	*Energy Harvesting System*
EMI	*Electromagnetic Interference*
FOS	*Fiber Optic Sensor*
HREE	*Heavy Rare Earth Elements*
IoT	*Internet of Things*
IR	*Import Reliance*
KPI	*Key Performance Indicator*
LCA	*Life Cycle Assessment*
LCCA	*Life Cycle Cost Analysis*
LREE	*Light Rare Earth Elements*
MBE	*Molecular Beam Epitaxy*
MCU	*Microcontroller Unit*
MOCVD	*Metal Organic Chemical Vapor Deposition*
PCB	*Printed Circuit Board*
PE	*Piezoelectric*
PEG	*Piezoelectric Generator*
SC	*Supercapacitor*
SHM	*Structural Health Monitoring*
SoA	*State of the Art*
SR	*Supply Risk*
TBD	*To be Defined*
TE	*Thermoelectric*
TEG	*Thermoelectric Generator*
TPEG	*Thermo-piezoelectric Generator*
UV	*Ultaviolet*
VA	*Value Added*
WP	*Work Package*

1 Key Performance Indicators

This deliverable encases the Key Performance Indicators (KPIs) that were defined at the beginning of the project (WP1, T1.2 - SMRT). These KPI will be taken as a reference baseline for the assessment of the obtained results regarding the smart materials and systems developed in InComEss. The performance of the researched systems can be compared to the projected goals, which shall indicate a "quantifiable" success trend. The KPIs are separated in:

- *Materials* (mainly applicable for WP2…WP4) to characterize the new materials solutions and to allow for comparison between these materials and the benchmarked commercial and SoA solutions
- *Systems* (WP5…WP7) where quantifying the performance of each component (energy generators, energy storage supercapacitors (SCs) and power conditioning unit) and the whole system are defined

SMRT has been the responsible for data gathering regarding state-of-the-art materials and Systems as reference. The partners involved in this task, in charge of the manufacturing processes for the piezoelectric composite fibres (AIMEN, CeNTi, SMRT, NCYL – WP2), thermoelectric composite materials (IPF, NCYL, AIMEN – WP3) and supercapacitors (TAU, CeNTI, SKLT - WP4) and ,have given inputs of relevant KPIs for the success goal indicators regarding these as a "single component". Furthermore, partners involved in the use-case scenarios (FOCC, MARELLI, SONA – WP7) and IoT (ICCS – WP6) have contributed with their feedback for goal parameters that help dimension the materials as a complete assembly.

The projected goals parting from test results and the reference parameters were set in table form. These shall be further categorized and in the upcoming body displayed and briefly explained.

Apart from the KPIs, the critical raw materials used in the baselines were analysed from availability and dependency risk for Piezoelectric, Thermoelectric and Supercapacitor by CIRCE. This availability will be also compared in WP8 for the raw materials used in InComEss' innovative products. Moreover, dependency analysis carried out by CIRCE in task T1.2 will be compared in WP8 considering in terms of geological availability and geopolitical stability, expecting a dependency risk reduction compared to baseline and monetary savings when critical raw materials are avoided.

2 Materials KPIs

Specification

Material-defined key performance indicators are mainly focused on the manufacturing side of the components for the energy harvesting units. This encases the physical, piezoelectric (PE) and thermoelectric (TE), mechanical and performance traits of the key components for the energy generators (PEG & TEG) as well as for the supercapacitors (SCs).

2.1 Advanced Lead-Free Piezoelectric Composite Fibres for Mechanical Harvesting (PEG)

The piezoelectric composite fibres are to be used as electrical energy generators through experiencing mechanical strain. These are characterized as following, considering their mechanical and piezoelectric performance, manufacturability traits, stability as well as the geological availability and geopolitical stability.

Table 2. 1 KPIs for Piezoelectric Composite Fibres

KPI name	KPI #	Test Environment	SoA (ref. value)	Target (success indicator)
Piezoelectric voltage coefficient (g31, g33)	1	Laboratory	220 mVm/N	>250 mVm/N
Piezoelectric strain coefficient (d31, d33)	2	Laboratory	20 pC/N	30 pC/N
Electromechanical coupling (kij)	3	Laboratory	0.5	>0.5
Strain (%)	4	Laboratory	0.002	0.35
Fibre flexibility	5	Laboratory	Ceramic based (rigid)	Polymeric composite (flexible)
Fibre straightness	6	Laboratory	Composite fibres embedding large volume fraction (60%)	Composite fibres embedding low volume fraction (15%)
Cycle stability (number of cycles)	7	Laboratory	Piezo-patch operational lifetime of ≥10E+07 cycles @ 0.15 compression, 10Hz & with optimal resistance load	Same
Thermal stability (°C)	8	Laboratory	Flexible PVDF limited by curie temperature up to 90 ºC / rigid Ceramic based BaTiO3 130 ºC / rigid ZnO is a pyroelectric material	>90 ºC

Adhesion fibre-epoxy matrix	9	Laboratory	Optical inspection – no ‘pull-out’ test since low tensile strength of the fibre	<10% of failed interface length after testing
Cost reduction (%)	10	Desk Work	N/A	Economically viable prices for use cases. Few process steps, automatized steps where needed
Up-cyclability [%]	11	Theoretical and laboratory tests (T8.2)	No	To be defined in further manufacturing steps
Dependency risk [%]	12	Theoretical and laboratory tests (T8.2)	Lead zirconate titanate solid solutions	<5% REE and CRM composition
Material loss [%]	13	Production facilities	6% waste for melt-spinning process	6% waste for melt-spinning process

2.2 Advanced Melt-Mixed Polymer Composites for Harvesting of Heat Wasted (TEG)

The TEG produces electrical energy though experiencing thermal stress. Therefore, the input/output electrical, chemical and thermal parameters are considered for the TEG, as well as some geological availability and geopolitical stability parameters.

Table 2. 2. KPIs for Thermoelectric Generator

Electrical conductivity	KPI #	Test Environment	SoA (ref. value)	Target (success indicator
Electrical conductivity	14	Laboratory	72.1 S/m (PBT/SWCNT); 64.6 S/m (PA6/SWCNT) (Ref. J. Compos. Sci. 2019, 3, 106)	100 S/m
Seebeck coefficient	15	Laboratory	62.3 µV/K (PBT/SWCNT); -47.0 µV/K (PA6/SWCNT) (Ref. J. Compos. Sci. 2019, 3, 106)	+/- 70 µV/K
Power factor	16	Laboratory	0.2797 µW/m·K^2 (PBT/SWCNT); 0.1425 µW/m·K^2 (PA6/SWCNT) (Ref. J. Compos. Sci. 2019, 3, 106)	0.5 µW/m·K^2
Chemical stability	17	Laboratory	N/A	The chemical stability of polymers should be very

				good against most chemicals. The requirements depend on the environment in the application. - **Yes** for environmental chemicals in use case scenarios- Coating might be needed in further step processes
Operating temperatures	18	Laboratory	PBT: -50°C … 140°C (150°C); PA6: -40°C … 85°C (160°C)	-50°C …. 240°C
Long-term stability	19	Laboratory	Power factor was reduced to 35% of the initial value (PP+0.8 wt% CNT+5 wt% CuO+4 wt% PEG, J. Luo et al. Polymer 108 (2017) 513-520)	After 6 months of storage the power factor should still be at least 80% of the initial value.
Cost reduction	20	Desk Work	No price available due to the novelty of the construction	Economically viable prices for use cases. Few process steps, automatized steps where needed
Up-cyclability [%]	21	Theoretical and laboratory tests (T8.2)	No	To be defined in further manufacturing steps
Dependency risk [%]	22	Theoretical and laboratory tests (T8.2)	No	<10%
Detachability	23	Laboratory	No reference	To be defined in further manufacturing steps
Reusability	24	Laboratory	No reference	To be defined in further manufacturing steps
Down-cyclability [%]	25	Laboratory	N/A	Rest-energy from burning
Material loss [%]	26	Production facilities	About 95% of composite material produced can be used, losses are only caused by cutting at the edges	About 95% of composite material produced can be used, losses are only caused by cutting at the edges

2.3 Monolithic Supercapacitors for Energy Storage

The supercapacitors created for this project are intended for energy buffering as type of battery. The energy they can store will impact the amount of energy one energy harvesting system can provide to the sensor nodes for the end-use cases. The mechanical characteristics are also of importance given the possibility of them experiencing mechanical stress withing the energy harvesting system.

Therefore, the electrical characteristics as well as the mechanical ones are taken into account for the KPIs, as well as some geological availability and geopolitical stability parameters.

Table 2. 3. KPIs for Supercapacitors

KPI name	KPI #	Test Environment	SoA (ref. value)	Target (success indicator
Specific capacitance - electrodes & supercapacitor	27	Laboratory	290 F/g	400 F/g
Energy density	28	Laboratory	5 Wh/kg (commercial SoA). 1.7 (IPF material)	5 Wh/kg (flexible environmentally friendly material)
Power density	29	Laboratory	4 kW/kg (0.2 IPF)	5 kW/kg
Cycle stability	30	Laboratory	80 % after 1000 cycles	90 % after 5000 cycles
Electrical conductivity - electrolytes	31	Laboratory	0.1 S/cm (liquid)	0.2 S/cm (liquid)
Operation voltage window – electrolytes	32	Laboratory	2.5 - 2.8 V	up to 3 V
Leakage (µA/F)	33	Laboratory	N/A	20 µA/F after 1 hour at 0.8 V
Volumetric capacitance, single electrode level	34	Laboratory	80 F/cc	120 F/cc
Voltage hold lifetime at maximum operative voltage	35	Laboratory	N/A	1500h (at max specified temp)
Cost reduction - electrodes & supercapacitor	36	Laboratory	€0.08	€0.04
Flexibility	37	Laboratory	Bending diameter 2.5cm for 1 cell (1V)	Bending diameter 2.5cm for 3 cells in series (3V)
Down-cyclability	38	Laboratory	No reference	Energy gain through burning of components + recovery of electrode materials
Material loss [%]	39	Production facilities	20% use / 80 % waste	80 % use / 20 % waste

3 System Specific KPIs

Specification

The second section for the KPIs is specifically for the characterization of the energy harvesting Systems as a whole, rather than their specific components. Through the definition of the different use-cases necessities, their individual system characteristics shall help define an appropriate energy harvesting system with case-specific specs. These shall be marked as a baseline to follow throughout the project.

3.1 Configuration Design of Generators and Lab-Scale Prototyping

Given the novelty of the construction of the TE composites, there are no reference values to which the success indicators can be defined. Therefore, this section is mainly focused on the characterization of the KPIs for the piezoelectric generator (PEG) taking into account the knowledge and experience of SMRT in the manufacturing of piezoelectric patches. The targeted values are selected taking into account a set of pre-defined influencing parameters that will help keep a consistent standard with a point of reference.

An extra table for the TEG has been integrated within this document, however, given that there are still no reference values at this stage of the project, all parameters are set blank and will be later defined at the end of WP3 and/or begin of WP5 when the single TE composite materials are defined and measured. This will provide a sort of feedback as to what to expect with a single patch and create a contrast with the real values.

Table 3. 1. KPIs for PE Energy Generators

KPI name	KPI #	Test Environment	SoA (ref. value)	Target (success indicator
Energy output PEG (µWs)	40	Laboratory	500 µWs @400 ppm, 10 Hz, 4 cm²	>500 µWs @400 ppm, 10 Hz, 4 cm²
PEG Frequency-impedance ratio - PEG	41	Laboratory	~1.2 MOhm @10 Hz, 4cm²	≤1.2 MOhm @10 Hz, 4cm²
Tensile Modulus E1 PE Patches	42	Laboratory	30.336 GPa	30.336 GPa ±10% (might change depending on single fibre characteristics)
Tensile Modulus E2 PE Patches	43	Laboratory	15.857 GPa	15.857 GPa ±10% (might change depending on single fibre characteristics)
Poisson's Ratio, v12 PE Patches	44	Laboratory	0.31	0.31 ± 10% (might change depending on single fibre characteristics)
Poisson's Ratio, v21 PE Patches	45	Laboratory	0.16	0.16 ± 10% (might change depending on single fibre characteristics)

PE Patch dimensions (Length x Width in mm)	46	Laboratory	85mm x 85mm	85mm x 85mm possible
Capacitance (85x85mm Patch)	47	Laboratory	970 nF	970 nF ±20%

Table 3. 2. KPIs for TE Energy Generators

KPI name	KPI #	Test Environment	SoA (ref. value)	Target (success indicator
Open Circuit Voltage V_{OC} (V)	48	Laboratory	N/A	To be defined at end of WP3 & Start of WP5
Short Circuit Current I_{SC} (A)	49	Laboratory	N/A	To be defined at end of WP3 & Start of WP5
Voltage at max. Power V_{mp} (V)	50	Laboratory	N/A	To be defined at end of WP3 & Start of WP5
Current at max. Power I_{mp} (A)	51	Laboratory	N/A	To be defined at end of WP3 & Start of WP5
Max. Power P_{max} (W)	52	Laboratory	N/A	To be defined at end of WP3 & Start of WP5
TEG Patch dimensions (Length x Width in mm)	53	Laboratory	N/A	To be defined at end of WP3 & Start of WP5

Regarding the TPEG there is an unforeseeable complexity of the structure, seen as though there is no previously established hybrid generator of this sort. Values with which one can set aim on are consequently inexistent and hard to estimate. Given that both composite materials are to be combined in one generator, the KPIs table for the hybrid generator (TPEG) are to be created first when the PE composite fibres and TE composite materials are completed at the end of WP2 and WP3 and beginning of WP5.

3.2 Power Conditioner, Wireless Sensor Nodes and IoT

The power conditioning unit for the generators, as well as the sensors and IoT nodes are key elements of the EHS. These elements can help define the limits for the system, mainly considering the energy balance from the energy generated to the energy needed for the end use cases. The energy and power consumption of these elements is considered in the following table.

Table 3. 3. KPIs for PCC, WSN & IoT

KPI name	KPI #	Test Environment	SoA (ref. value)	Target (success indicator
Power consumption during sleep (µW) - MCU Conditioner	54	Laboratory	0,3µA*3,6V=0,97µW @STM32L0x0	Same

Power consumption active mode (µW) - MCU	55	Laboratory	87µA*3,6V=349µW @STM32L0x0	Same
Energy consumption (%) conditioner vs. Input energy	56	Laboratory	~25-33%	60%
Energy consumption (µWs) - FOS	57	Laboratory	4µA*3.6V=14.4µW during sleep + 100mJ per measurement burst	Ability to perform at least 1 measurement per day, powered by harvested energy.
Data transmission distance (m) - WSN	58	Laboratory	Bluetooth LE: 50m (100m LoS on protocol); LoRaWAN: ~10km	Scenario dependent: eventually defining parameter for aeronautic scenario through sender-receiver distance and receiver type. Bluetooth LE: 50m max. LoRaWAN: any distance
Power consumption (µW/s) - WSN	59	Laboratory	~15mA for Bluetooth LoRaWAN not pre-definable	<15mA Bluetooth LoRaWAN definable at later development stages due to unknow data rate

3.3 Systems Integration and Demonstration

There are three different end-use scenarios, defined by a building façade (PEG used), an automotive case (TEG used), and an aeronautic case (TPEG used). Seen as though these three end-user scenarios have different generator types as well as different goals and conditions, the energy harvesting unit's end design might be affected according to the scenarios. Some scenario-dependant key performance indicators are defined in the following section.

3.4 Demonstration of PE-EHS for the Building Use-Case

Table 3. 4. KPIs for Building Use-Case

KPI name	KPI #	Test Environment	SoA (ref. value)	Target (success indicator
System's resistance to UV light	60	Laboratory	N/A	Coating of UV exposed parts with UV resistant materials possible
System's resistance to chemical components of water and air in the environment	61	Laboratory	YES	YES
Wind load resistance	62	Façade testing facility	Wind load to be defined. Maximum operational tensile	Wind load range for PEG energy production [to be defined]

			strength of <4500ppm on the piezo patch	Facade components frequency range for PEG energy production [to be defined] Maximum wind load for PEG resistance [to be defined]
IoT Platform	63	Façade testing facility	N/A	YES
Energy production and storage	64	Façade testing facility	N/A	Demo case dependent: 0,03 (IoT)…50,4 (probe network) Wh/day
Cost optimization	65	Desk activity	N/A	YES

3.5 Demonstration of TE-EHS for the Automotive Use-Case

Table 3. 5. KPIs for Automotive Use-Case

KPI name	KPI #	Test Environment	SoA (ref. value)	Target (success indicator
Applied pressure on TEM during installation	66	Laboratory	N/A	To be defined with TEM manufacturer partner at later stages
Road vibration resistance	67	Laboratory	N/A	Power output reduction <5%
High adhesion stability against thermal stress	68	Laboratory	Different types of adhesives and mechanical solutions already available in the market	Adhesive or mechanical solution, which does not affect TEG's performance (High thermal conductivity, low mechanical stress) and resistant to peak Temperatures of ~300°C
Flexibility / Integration / dimensions	69	Laboratory	N/A	Patch dimensions fit within given limited space, and bend according to surface form of structure
Patch Thickness (mm)	70	Laboratory	N/A	Low thickness desired to fit generator in difficult places with increased flexibility
Operational condition efficiency	71	Laboratory	N/A	Generate enough energy (TBD) to power SHM or any kind of sensors based on normal operating conditions

Thermal fatigue resistance	72	Laboratory	N/A	Power output reduction <10%

3.6 Demonstration of TPE-EHS for the Aeronautic Use-Case

Table 3. 6. KPIs for Aeronautic Use-Case

KPI name	KPI #	Test Environment	SoA (ref. value)	Target (success indicator
Thermal conductivity from the TPEG patch (W/(m*K))	73	Laboratory	N/A	A typical Epoxy value of 4 (W/m/K) is proposed as first estimation.
Patch Thickness (mm)	74	Laboratory	N/A	No minimum thickness (0.1 mm typical for composite ply) Low thickness desired to increase location possibilities as well as flexibility of patches
Bonding materials' adhesive strength (N/mm²)	75	Laboratory	'Peel strength (around 4 N/mm or 100 N + Cohesive failure mode) and a shear strength (around 28 MPa + Cohesive failure mode) in different conditions: at -55°C and RT without preliminary conditioning, at high temperature (80°C) after hot and wet conditioning (70°C/85%RH for 2000 hours) (Reference values for structural bonding - could be reviewed for non-structural bonding)	Peel strength (around 4 N/mm or 100 N) and a shear strength (around 28 MPa) in different conditions: at -55°C and RT without preliminary conditioning, at high temperature (80°C) after hot and wet conditioning (70°C/85%RH for 2000 hours) Failure mode analysis to help identify a problem: surface preparation, non-adapted adhesive/adhesive-substrate compatibility or problem inherent to the TPEG or component itself
EMI from the TPE-EHS	76	Laboratory	The TEG System shall be neither affected by surrounding electromagnetic interference (EMI) due to its installation on the aircraft nor cause interference to other equipment or electrical networks.	The TEG System shall be neither affected by surrounding electromagnetic interference (EMI) due to its installation on the aircraft nor cause interference to other equipment or electrical networks.

Flexibility / Integration / dimensions	77	Laboratory	N/A	Patch dimensions fit within given limited space, and bend according to surface form of structure. TPEG-EHS systems shall not affect/degrade the performances of the aeronautical part (de-icing, aerodynamism, mechanical performances…)
Standardized system	78	Laboratory	N/A	System adapted to both metallic and composite structure Material compatibility at 180°C curing cycle during system-composite integration through composite part molding Bonding afterwards also possible, but this should not affect integrity of the whole system (some bonding system require 120°C/180°C curing)
Respect of the technical requirements	79	Laboratory	N/A	Fulfilment of mentioned requirements in D1.3 and "SONA requirements document" for TPEG
SHM	80	Laboratory	N/A	Possibility to be used for: Temperature measurement, risk of failure detection (piccolo tube), failure propagation monitoring of structural metallic or composite part, constraint gages, pressure gages, composite material health monitoring: impact, failure, delamination
Operational condition efficiency	81	Laboratory	No values regarding efficiency => depends on the further	Generate enough energy (TBD) to power SHM or any kind of sensors

			application (SHM/type of sensors) Values regarding operational conditions to activate TPEG system given and explained as part of Deliverable D1.3	based on normal operating conditions.
Durability	82	Laboratory	N/A	Durability is typically defined regarding the flight time. Requirements are different for structural parts (which is the case of the support) and non-structural part, accessibility for maintenance/replacement Specific values to be defined at later stages
Maintenance cost/needs	83	Laboratory	Visual alert in case of misfunctioning Check/maintenance every X flight hours (X = TBD).	Limit the maintenance time and cost Avoid risk of aircraft stops

4 LCA InComEss materials baseline, geological availability and geopolitical stability

4.1 Setting Baseline scenarios for LCA studies

CIRCE has been in charge of the Baseline scenarios for LCA studies in collaboration with the partners involved on the development of piezoelectric, thermoelectric and supercapacitor materials which will be developed in InComEss. Briefly, Life Cycle Assessment is a methodology based on ISO 14040 and 14044 that can provide the environmental impact of some product or service under a myriad of indicators. In order to test that InComEss' innovative products lead to an environmental and/or economic improvement it is necessary to set a baseline to set a reference value. In this way, the LCA results for innovations could be compared to some scenario (product). In this section the baselines (the products) that will be used as reference in WP8 for LCA/LCC purposes are defined.

In order to define a methodology to gather all the required data a "data gathering protocol" has been generated by CIRCE and shared with involved partners. This protocol can be found in ANNEX II.

Herein, three types of baselines have been addressed by CIRCE for 1) piezoelectric generator, 2) thermoelectric materials and 3) supercapacitors.

4.1.1 Piezoelectric Generator baseline

Nowadays, most of the piezoelectric generators (PEG) include the use of lead-based PZT ceramics, which are toxic and have a large environmental impact[1]. Therefore, the manufacturing of a more sustainable, non-toxic though high performance alternative is a key target of the InComEss project since the piezoelectric composite fibres developed in InComEss are lead-free and therefore, environmentally friendly.

For the baseline piezoelectric generator production, a piezo wafer made of PZT is used and fibres with the required width are cut with help of a circular saw.

In parallel, the contacts from two flexible Printed Circuit Boards (PCB), used for the top and bottom layers of the PEG, each with the structured electrodes, are pre-tinned with solder tin. Then, the PCB layer designated for the bottom part of the patch gets pre-impregnated with epoxy, and the piezo fibres are then aligned onto it and continues then to a pre-curing process, with a press with the action of heat. The top flex-PCB gets pre-impregnated with epoxy too and placed onto the bottom of pre-cured PCB layer with the piezoelectric (PE) fibres already aligned onto it.

The assembled Bottom flexible PCB - epoxy\\ PZT Fibres\\epoxy - Top flexible PCB continues to be cured with heat, adhering all components together. The patch then gets polarized with an appropriate voltage of 2 - 3kV/mm, generating the final piezoelectric generator as an end-product.

In Figure 4.1 the baseline production process that will be used as reference scenario is drawn.

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[1] EU-Directive 2011/65/EU, "Restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS)," Official Journal of the European Union L174, 88 (2011).

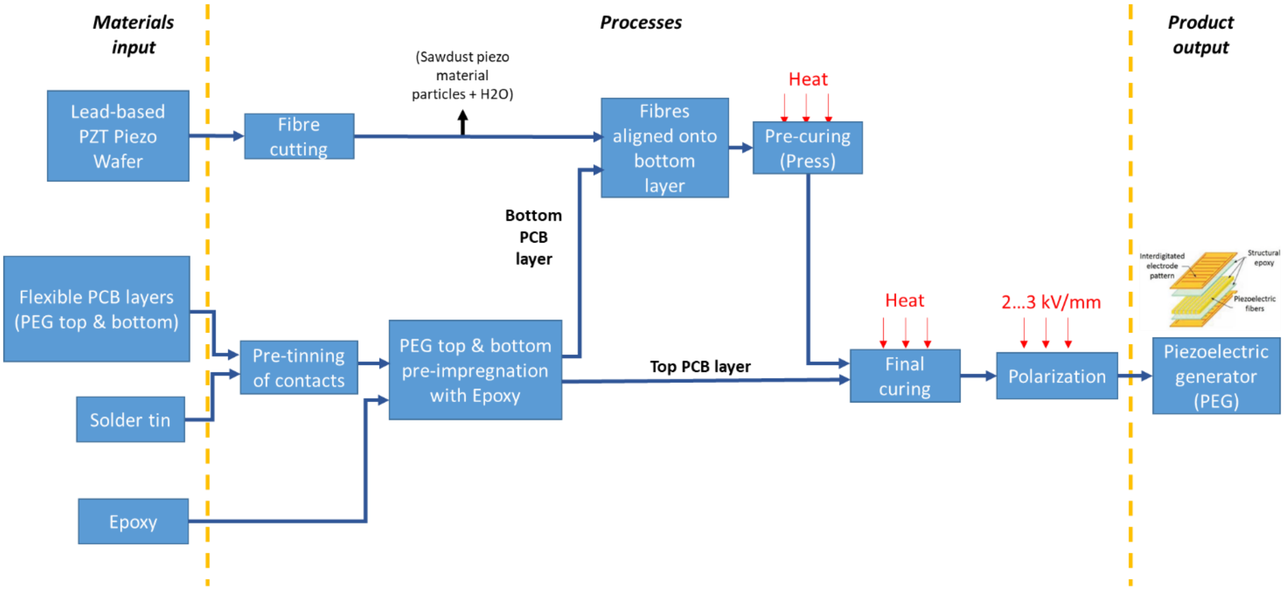

Figure 4.1: PEG baseline manufacturing process. Source: SMRT

InComEss' partner SMRT is currently producing these piezoelectric generators and will provide the necessary Life Cycle Inventory data for the evaluation of the environmental impact, which will be calculated with the ReCiPe methodology. The objective of the ReCiPe method is to transform the list of Life Cycle Inventory data, into a limited number of indicator scores. These indicator scores express the relative severity on an environmental impact category. CIRCE will continue the gathering of inventory data to assess the environmental impact of the SMRT's baseline in order to compare the results with WP8 studies.

4.1.2 Thermoelectric materials baseline

Thermoelectric (TE) materials are materials under intensive research because of their dual capability of directly converting heat into electricity or electrical power into cooling or heating. These materials can play an important role in reducing carbon emission by converting waste heat into electricity.

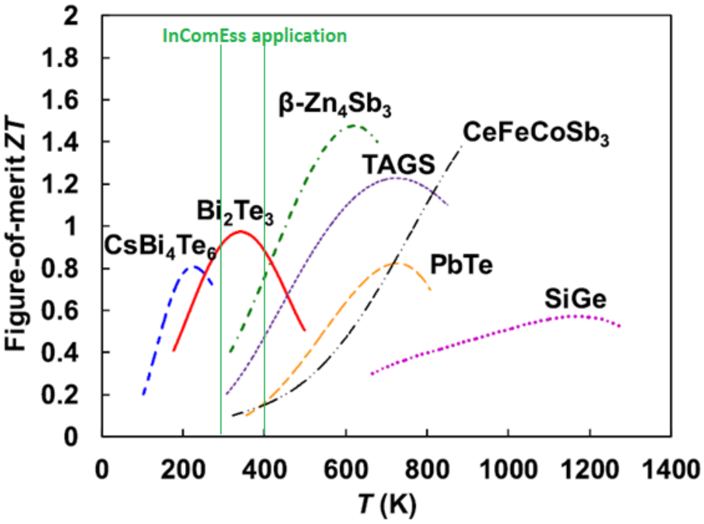

Figure 4.2: Efficiency of thermoelectric generation by material[2].

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[2] C. Uher, "Skutterudite-based thermoelectrics," in Thermoelectrics Handbook—Macro to Nano , Florida, CRC Press, 2006, pp. 34-1 to 34-17.

At a first glance, in order to define a baseline scenario to compare InComEss' TE materials a literature revision was performed based on the figure-of-merit (ZT) parameter (measuring the maximum efficiency of thermoelectric generation by a particular material) versus the temperature application. For the InComEss application the temperatures are assumed to be ranged from -50ºC to 298ºC. In Figure 4.2 it is possible to see that at these temperatures the most efficient TE material is the Bismuth telluride (Bi_2Te_3) and its alloys. This material has been consequently chosen as a baseline product to compare with the thermoplastic and carbon-based materials employed for the InComEss project, given the fact of it being the best-known TE material for ambient temperature applications[3].

Considering the InComEss applications and the expected characteristics of the new TE material (flexible and able to be integrated and based on thermoplastic and carbon materials) the selected manufacturing process to be used as baseline has been the thin film technology. Traditional thermoelectric devices are fabricated from sintered blocks of the materials. However, there are certain difficulties and limitations in making highly miniaturized devices due to the cutting and assembling processes. Thin film technology has different manufacturing processes: flash evaporation, co-sputtering, pulsed laser deposition, metal organic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE). In this case, the flash evaporation manufacturing process was selected as baseline scenario to produce a Bismuth-Telluride-based alloy because it presents the lowest and easiest way to produce TE materials[4].

In Figure 4.3 a vacuum chamber is presented for flash evaporation. Power requirements for vacuum Tungsten mass for boa, the stainless steel for the guide, the Teflon for easing the power discharge and power required to reach over 200ºC will be considered in DLV 8.3 for LCA.

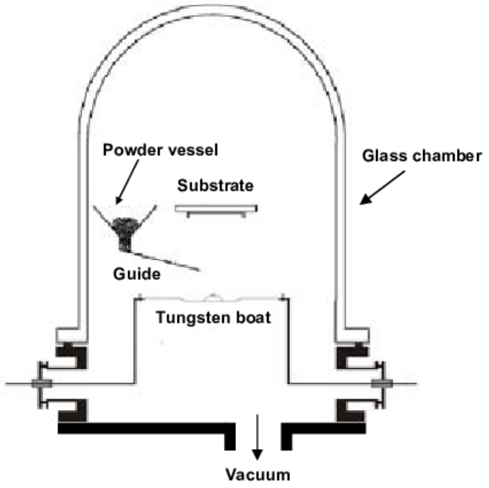

Figure 4.3: Vacuum chamber prepared for Flash evaporation[5].

4.1.3 Supercapacitors baseline

One of the most conventional technology used for energy storage are Li-ion batteries, which have a high environmental impact throughout their life cycle through the use of critical resources such as

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[3] M. Saleemi, M. Toprak, S. Li, M. Johnsson and M. Muhammed, "Synthesis, processing, and thermoelectric properties of bulk nanostructured bismuth telluride (Bi2Te3)," Journal of Materials Chemistry, pp. 725-730, 2012.

[4] M. Takashiri, T. Shirakawa, K. Miyazaki, H. Tsukamoto. Fabrication and characterization of bismuth–telluride-based alloy thin film thermoelectric generators by flash evaporation method. Sensors and Actuators A: Physical 138 (2007), Pp. 329-334

[5] L.M. Gonçalves. The deposition of Bi2Te3and Sb2Te3 Thermoelectric thin-films by thermal Co-evaporation and applications in Energy Harvesting.

Lithium and cobalt. In the InComEss project, supercapacitors (SC) have been proposed as a more environmentally friendly solution to replace batteries due to their high durability and because the supercapacitors fabricated in InComEss are polymer-based and therefore, more recyclable.

To establish the baseline of the reference supercapacitors, all input flows (raw materials, energy, transport) and output flows (products, by-products, residues, emissions) have been considered based on SKLT inputs. The manufacturing process for ultracapacitors is shown in the following Figure 4.4. The use of Li-ion batteries was also considered as a baseline even though no manufacturers are present in the consortium and the energy density of Li-ion batteries and the expected values (according to KPIs) for the innovation SC are not comparable in term of magnitude.

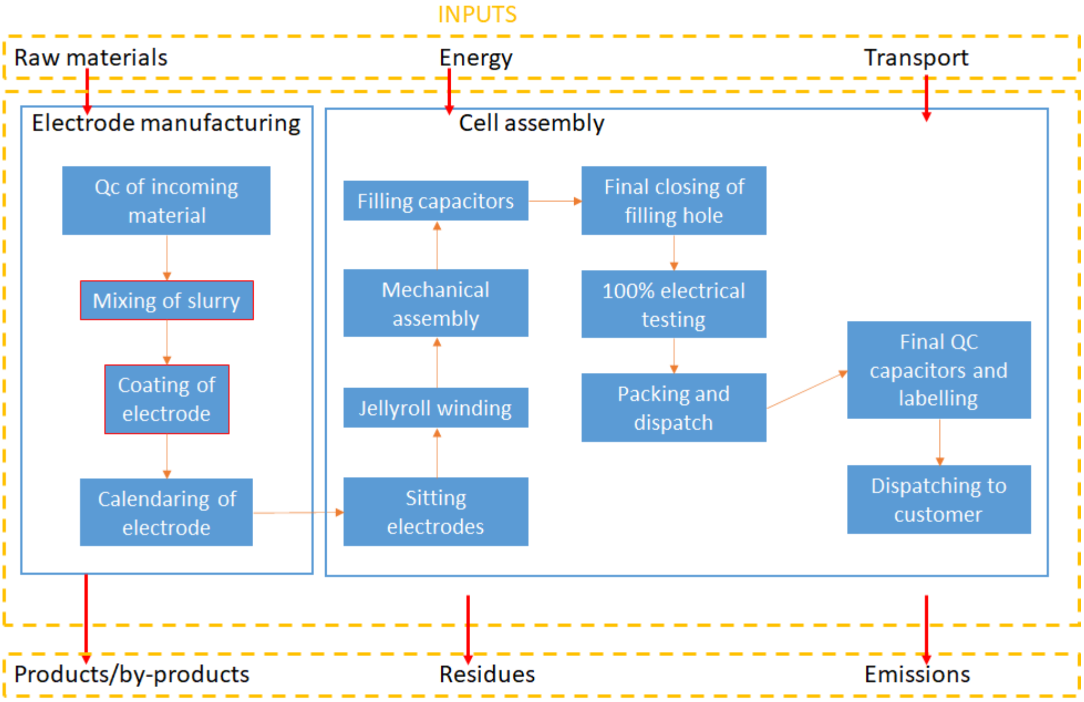

Figure 4.4: SKLT manufacturing process for UC baseline product.

The first stage of the process involves the manufacture of the electrode, which is mainly composed of a slurry of a carbon material and aluminium foil. Subsequently, the electrodes, separators and electrolytes are assembled to form the ultracapacitor cell. Finally, this cell is tested and packaged to be dispatched to the customer.

Based on the data provided by SKLT about the manufacturing process, an inventory has been prepared that includes all inputs and outputs involved production of a supercapacitor cell. This inventory will be used in WP8 in order to obtain the baseline environmental impact and can be found in ANNEX III.

4.2 Risk dependency analysis

This section comprises the study CIRCE has been carried out in task T1.2 on dependency analysis considering geological availability and geopolitical stability, expecting a dependency risk reduction compared to baseline and monetary savings when critical raw materials are avoided. This study will be used as baseline for WP8 dedicated to LCA and LCC.

Based on the baseline scenarios definition and the expected materials to be used in the InComEss' innovations the following materials were considered in terms of risk dependency:

- Lead for Piezoelectric baseline (PZT)
- Zinc, Barium and Titanium for Piezoelectric innovation (corresponding to the ZnO, $BaTiO_3$ particles employed for the development of lead-free PE composite fibres)
- Bismuth, Tellurium and Antimony for Thermoelectric baseline
- Aluminium foil for Supercapacitor baseline

Materials used in the baseline are compared in terms of criticality with the current expected materials to be used in the innovations. This is Pb, Bi, Te, Sb and Al (baseline) are included here and compared to Zn, Ba and Ti (innovations). In the WP8, once the final materials are completely defined, a detailed analysis based on the dependency improvements will be performed.

Once defined the metals under study, the next step is to evaluate them from supply risk and economic importance to define them as critical or non-critical raw materials. To generate these both parameters first of all it is necessary to define them and then to consider how to evaluate them.

Supply risk reflects the risk of a disruption in the EU supply of the material. It is based on the concentration of primary supply from raw materials producing countries, considering their governance performance and trade aspects. Depending on the EU import reliance (IR), proportionally the 2 sets of the producing countries are considered — the global suppliers and the countries from which the EU is sourcing the raw materials. Supply Risk is measured at the 'bottleneck' stage of the material (extraction or processing), which presents the highest supply risk for the EU. Substitution and recycling are considered risk-reducing measures. The physical meaning of Supply risk is directly connected to reserves and resources definitions:

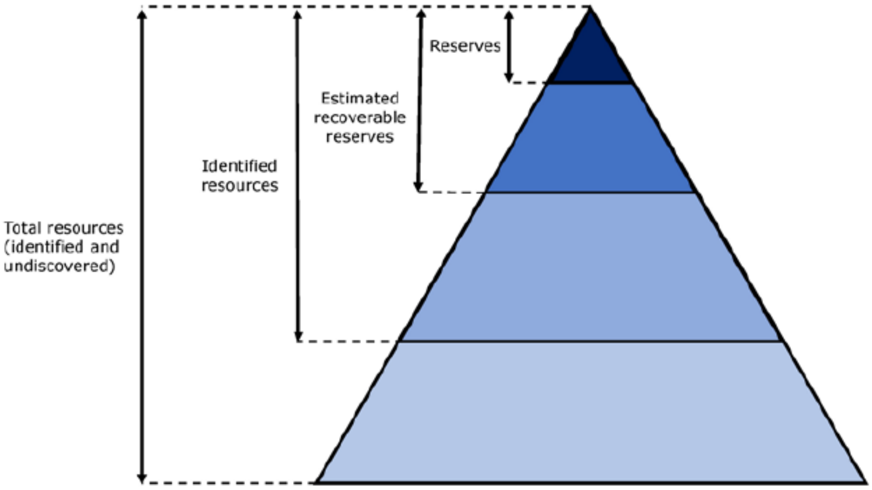

Figure 4.5. Reserves and resources physical description.

We can define resources as the total amount of a mineral that is present in the Earth's crust (disperse). This total amount is not directly accessible because of the low concentration and the actual costs of extraction for small concentrations. On the opposite, reserves are the total amount of a mineral that can be extracted under economical profitable conditions. So, resources will be probably available when extraction processes become cheaper of more efficient and/or reserves are extremely decreased.

Figure 4.6 shows the world production per year for different metallic commodities. This information is used for building up the Hubbert curves.

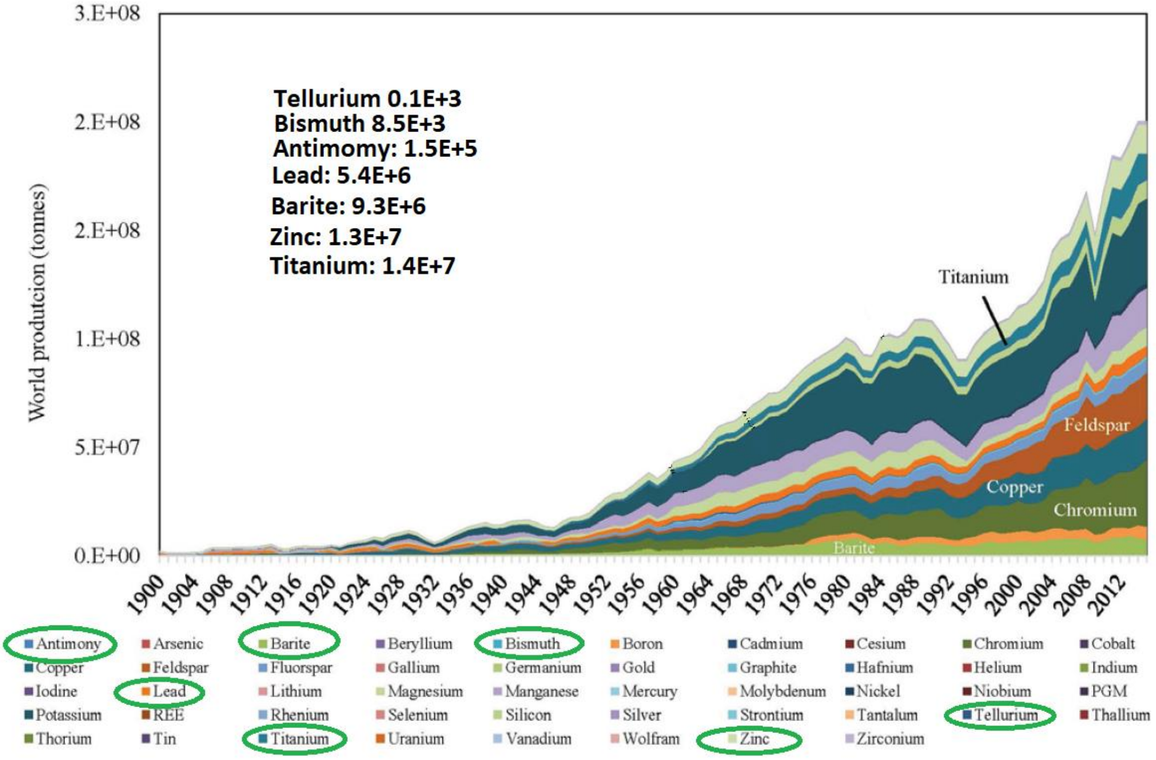

Figure 4.6: Metallic commodities worl production up to 2015.

This concept is like the petroleum peak concept (also known as Hubbert peak) and can be also translated to raw materials as see in Figure 4.7. We can see the maximum production ratio and when (year) will be reach the maximum production per year. Tellurium, as one of the studied materials reached the Hubbert peak in 2017.

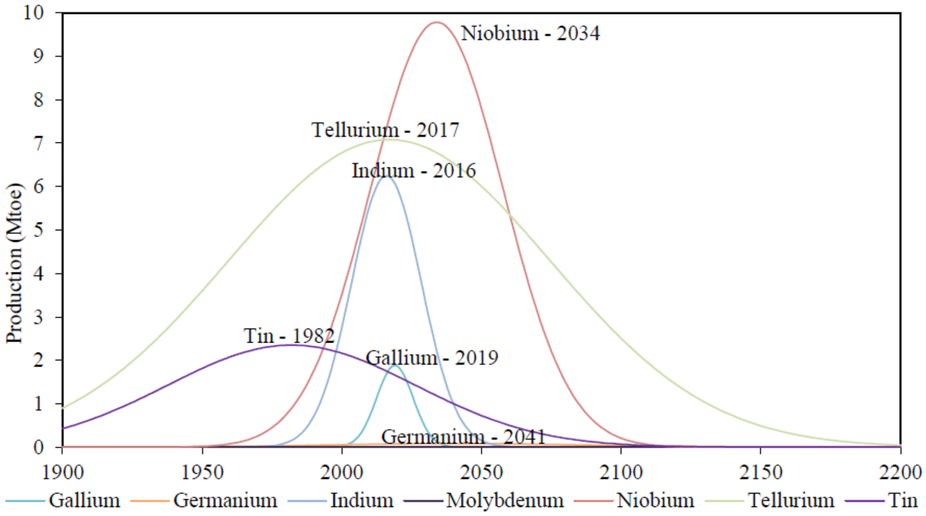

Figure 4.7: Hubbert's peak representation for some metallic commodities[6].

Economic importance aims at providing insight into the importance of a material for the EU economy in terms of end-use applications and the value added (VA) of corresponding EU manufacturing sectors at the NACE rev.2 (2-digit level). The economic importance is corrected by the substitution index (SIEI) related to technical and cost performance of the substitutes for individual applications.

Considering both parameters, it is possible to graph Supply risk vs Economic importance for different materials. EU Commission in 2017 updated the Critical Raw material list with 61 candidate materials (58 individual materials and 3 groups: Heavy Rare Earth Elements (HREE), Light Rare Earth Elements (LREE) and Platinum group. These candidates are depicted in Figure 4.8.

It is possible to identify critical raw materials according to the European Commission definition (SR >1 and EI > 2.8) because they are marked with red spots. InComEss' baseline related materials have been marked in purple. Three of them being identified as critical (Antimony, Bismuth and Baryte), and the rest of them critical only in economic terms (Tellurium, Zinc, Lead, Titanium and Aluminum). So, in terms of criticality, the thermoelectric materials generated in InComEss will be clearly an improvement in terms of risk dependency. Piezoelectric materials made of $BaTiO_3$ or ZnO will be a priori better in terms of environmental impact, but they are also linked to some critical and economic relevant materials (Baryte, Zinc and Titanium) so WP8 will put emphasis on metal recoveries.

In Table 4.1 it is possible to identify the InComEss related materials, the source, recycling ratio and criticality factors.

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[6] A. Valero and A. Valero Capilla. Thanatia: The Destiny Of The Earth's Mineral Resources - A Thermodynamic Cradle-to-cradle Assessment. 2014. World Scientific

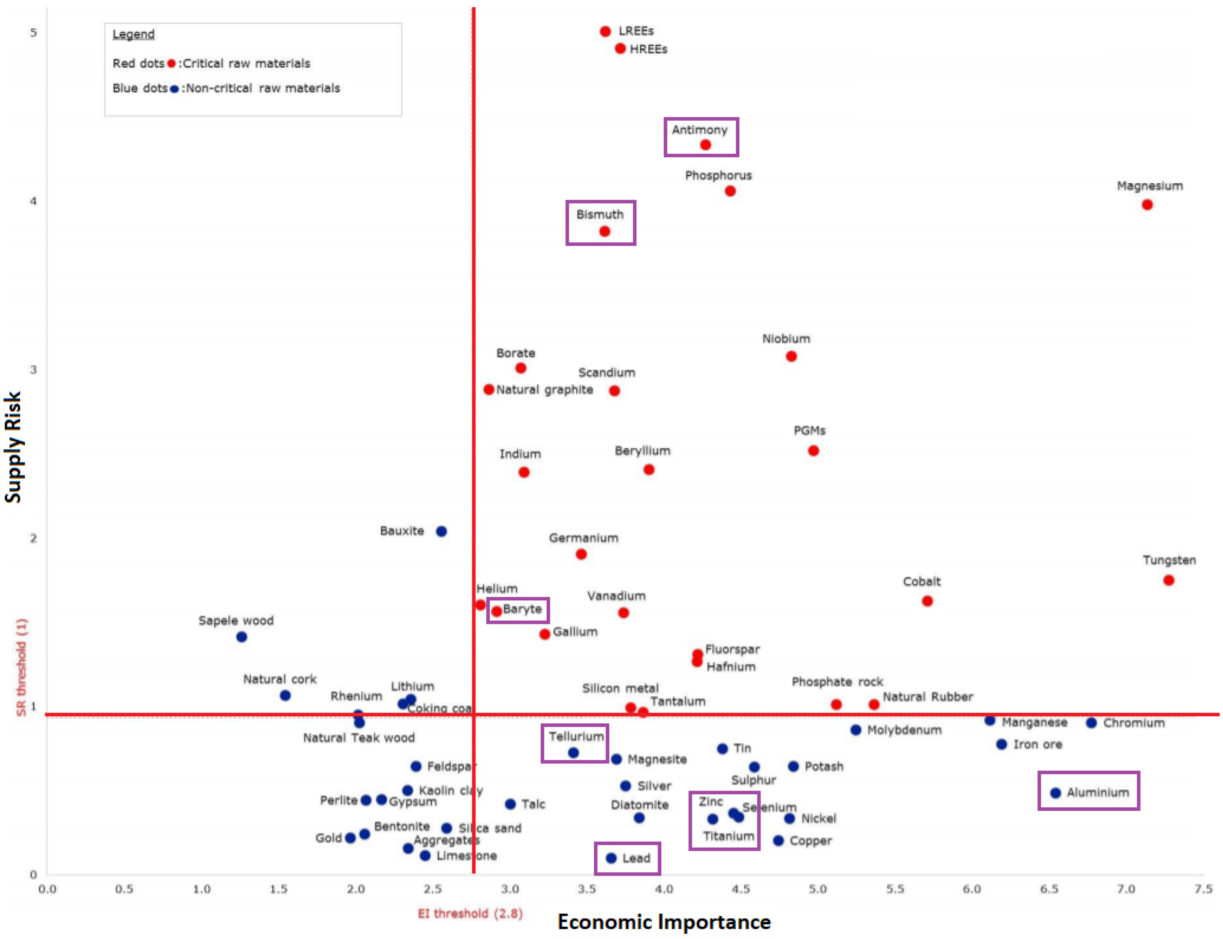

Figure 4.8: Economic importance and supply risk results of 2017 criticality assessment [7].

According to the previous figure, the highest SR value and Economic Importance, the highest risk dependency is obtained for a raw material. We must highlight that some of the raw materials, are located under the SR value set by EU commission to be considered as a risk material but presents an Economic Importance very large. One of the examples is the Titanium or the Aluminum. They are accessible but expensive or relevant in terms of monetary flows. Table 4.1 shows the aforementioned parameters for the raw metals related to the baseline of the InComEss components and the metals to be used for the project's components.

Table 4.1: Raw metals sources and criticality[6].

Metal	Source	Country	Reserves	Supply risk	Economic importance	EU import reliance	Recycling ratio
Lead (Pb)	Galena	China 50%	+190 MTon	0.1	3.7	18%	75%
Zinc	Metallic Zn	China 49%	230 MTon	0.3	4.5	61%	31%

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[7] Deloitte Sustainability, British Geological Survey, Bureau de Recherches Géologiques et Minières, Netherlands Organisation for Applied Scientific Research. Study on the review of the list of Critical Raw Materials. 2017. European Comission.

Barium	Baryte	China 44%	N/A	1.6	2.9	80%	1%
Titanium	Ilmenite	Russia 46%	66 kTon	0.3	4.3	100%	19%
Bismuth	Byproduct from lead/copper/tin production	China 82%	N/A	3.8	3.6	100%	1%
Tellurium	from anode sludges from the electrolytic refining of blister copper in a ratio (1.000 tons copper / 1 kg of tellurium	USA 44%	11.1 kTon	0.7	3.4	100%	1%
Antimony	Shulfide from ores	China 87%	N/A	4.3	4.3	100%	28%
Aluminium foil	From Aluminium metal	China 54%	28.000 MTon	0.5	6.5	64%	12%

There is an additional alternative in order to define critical raw materials, not directly linked to Supply risk / Economic importance indicators (i.e. geopolitical impact), that is based on sudden modification of status quo. Some examples:

- *Political instability:* An example can be found in the political/economic intervention of OPEC in 1973-4 and again in 1980 following the Iran-Iraq War is for instance argued to have prevented the Hubbert global peak oil prediction of 2000 from being correct (Almeida and Silva, 2009). Thus, as economists tend to argue, the interaction of supply and demand determines the equilibrium price path in a market economy.
- *Investment niche:* For example, gold is the most representative commodity whose production depends strongly on market speculation. Indeed, with the global economic instability and market price fluctuations, investment in gold has increased, as investors seek safe-havens. Other precious metals such as silver or platinum follow similar patterns of behaviour.
- *Environment and health factors*: certain minerals have proven to be dangerous for the environment and/or human health. Consequently, alternative, and safer options have been sought to replace the original substance in its application, leading to sharp reductions in its extraction. Obviously if there is no commercial interest in a mineral, there is no investment wasted in its exploration. Hence, real or perceived mineral scarcity often has an economic origin rather than a geological one. A clear example of this is that of mercury. Its decline in consumption, except for in small-scale gold mining, forced companies to curve and finally stop production, as is the case for the Spanish Almadén mine, once the leading producer, where mining ceased in 2003. Consequently, production is said to follow an economic-driven bell-shaped curve. Commodities with similar stories are those of arsenic, beryllium, antimony or radioactive minerals (mainly uranium and thorium).
- *By-product character:* when the mineral is a by-product (i.e. Tellurium), production decisions may be driven by the economics of the host-metal and hence the Hubbert curves do not necessarily follow typical bell-shaped curves. This aspect is especially pronounced at the local scale.

5 Conclusions

The targeted success indicators will serve the purpose of examining the quality of the end products in terms of the raw elements (piezoelectric composite fibres – WP2, thermoelectric composite materials – WP3, supercapacitors – WP4) and the resulting generators (PEG, TEG, TPEG) in WP5, as well as tracking performance indicators by the end-use EHS during and by the end of WP7. The KPIs will help provide a guideline for the assessment of the success of the project at each stage.

The parameters were specifically defined with a focus on all important areas affecting the success of the project, ranging from mechanical, physical, chemical, electrical, environmental and economic aspects of each component and module (where relevant). These will showcase the performance properties of the materials and modules. The consortium has the responsibility to review these KPIs throughout the whole project's timeframe, and if necessary, to adapt and update the current research findings.

The partners in charge of each component shall carry out relevant measurements that deliver the dimensions and magnitudes in question for each goal parameter and will then carry out a comparison between the expected values and the actual values. How large the deviation is between both values will then help distinguish and pronounce the positivity of the acquired results. Further comparison with SoA values can be carried out when applicable, creating a direct contrast to already established benchmarks.

In the case of the KPIs in WP2, WP3 and WP4 an estimate to the criticality that a deviation between values (expected to acquired) has towards the performance of the generators in WP5 shall be done (considering only the relevant parameters). Analogue to this, KPIs in WP5 shall be taken into account to weigh their possible influence on the Energy harvesting systems on WP7. This shall help create an optimization baseline for the products at each step of the project which will help shape the end product towards an optimal market-suitable energy harvesting system. The analysis for the KPIs should be ideally carried at latest by the end of each corresponding WP save for those dependent on later stages.

Furthermore, the LCA baselines have been defined during T1.2 and will serve as a baseline for WP8 with the data gathered from the tested EHSs manufactured in WP7. In addition, a geopolitical / dependency risk analysis has been initially performed considering the baselines and also the expected InComEss' innovations. In this way, PEG created during the project must be designed in a way that ensure that recycling rations for Ba, Ti and Zn are obtained in order to mitigate dependency and monetary risks. Further conclusions are expected to be obtained in WP8.

6 Annex I. KPI Definitions and Extra Commentaries

1. **Piezoelectric voltage coefficient (g31, g33) –** *The ratio of the electric field produced to the mechanical stress applied*
2. **Piezoelectric strain coefficient (d31, d33) –** *Mechanical strain produced by an applied electric field*
3. **Electromechanical coupling (kij) -** *Conversion of energy by the ceramic element from electrical to mechanical form or vice versa*
4. **Strain (%) –** *defined by the amount of deformation caused by a force load applied to the material in relation to the material's original length*
5. **Fibre flexibility -** *The fibre flexibility is a key indicator to the load bearing capacity of the Patches*
6. **Fibre straightness -** *How straight the fibres are help define packaging reliability and repeatability*
7. **Cycle stability (number of cycles) –** *Fibre's performance reduction after a defined amount of cycles*
8. **Thermal stability (°C) –** *Ability to resist function reduction (retain its original properties) under thermal stress*
9. **Adhesion fibre-epoxy matrix –** *Shows how well the fibres adhere to an epoxy matrix, making it suitable for flex patches. Continuous bending test and optical inspection under microscope for failed interface areas*
10. **Cost reduction (%)**
11. **Up-cyclability [%] -** *Weight (% over total weight) recovered able to be used for similar or better purposes (recyclability or up-cyclability) per unit of fibre unit weight at the end-of-life period*
12. **Dependency risk [%] -** *Weight (% over total weight) of rare-earths elements (REE) and Critical Raw Materials (CRM) per unit of fibre unit weight*
13. **Material loss [%] -** *Weight (% over total weight) of raw material discarded in order to produce one fibre unit weight*

14. **Electrical conductivity -** *Electrical conductivity (s) should be high. For composites is 100 S/m realistically achievable*
15. **Seebeck coefficient -** *Seebeck coefficient (S) value should be high; it indicates how much thermovoltage can be generated. The higher the S, the more thermovoltage can be generated*
16. **Power factor -** *The power factor (PF= s*S*S) is usually much smaller than one. It should be at least 1*
17. **Chemical stability -** *The chemical stability of polymers should be very good against most chemicals. The requirements depend on the environment in the application*
18. **Operating temperatures -** *Operation temperatures in aeronautic systems: -50°C … 120°C; Operation temperatures in automotive systems: 80°C …. 240°C (300°C)*
19. **Long-term stability -** *The material should be as stable as possible regarding its thermoelectrical parameters*

20. **Cost reduction -** *At the moment only the pure material price could be indicated, because the production costs for the thermoelectric generator are still unknown.*
21. **Up-cyclability [%] -** *Weight (% over total weight) recovered able to be used for similar or better purposes (recyclability or up-cyclability) per unit of fibre unit weight at the end-of-life period*
22. **Dependency risk [%] -** *Weight (% over total weight) of rare-earths elements (REE) and Critical Raw Materials (CRM) per unit of fibre unit weight*
23. **Detachability -** *Capacity of being detachable easily (lack of welding or special tools required)*
24. **Reusability -** *Capacity of being used for other purposes after use with no or small operations*
25. **Down-cyclability [%] -** *Weight (% over total weight) of material recovered able to be used for energy valorisation or worst quality applications per unit of fibre unit weight at the end-of-life period*
26. **Material loss [%] -** *Weight (% over total weight) of raw material discarded in order to produce one composite unit weight*

27. **Specific capacitance - electrodes & supercapacitor -** *F/g for single PANi electrode (active material)*
28. **Energy density -** *Wh/kg (mass of two electrodes including active material)*
29. **Power density -** *kW/kg (mass of two electrodes including active material)*
30. **Cycle stability -** *Capacity retention after number of charge/discharge cycles*
31. **Electrical conductivity – electrolytes -** *Ionic conductivity S/cm*
32. **Operation voltage window – electrolytes -** *Maximum stable operation voltage for the supercapacitor device limited by electrolyte/electrode decomposition*
33. **Leakage (μA/F) -** *How much current flows from the supercapacitor to the rest of the circuit while not in use*
34. **Volumetric capacitance, single electrode level –** *Capacitance per unit volume*
35. **Voltage hold lifetime at maximum operative voltage -**
36. **Cost reduction - electrodes & supercapacitor -** *€/1 F device, including materials (processing cost directly dependent on manufacturing quantity)*
37. **Flexibility -** *The supercapacitors are projected to be flexible, making them ideal to integrate with the generator's system. The flexibility from the supercaps should ideally be close to that of the generator's*
38. **Reusability -** *Capacity of being used for other purposes after use with no or small operations*
39. **Material loss [%] -** *Weight (% over total weight) of raw material discarded in order to produce one supercapacitor unit weight*

40. **Energy output PEG (μWs) -** *Excitation with a specified cycle and energy measurement across a specified load (Capacitor)*
41. **PEG Frequency-impedance ratio – PEG -** *Impedance relationship to vibration frequency. Lower impedance leads to a better impedance matching possibility*

42. **Tensile Modulus E1 PE Patches -** *Describes the relationship between mechanical stress and strain through a uniaxial deformation in the longitudinal direction (direction with the fibres)*
43. **Tensile Modulus E2 PE Patches -** *Describes the relationship between mechanical stress and strain through a uniaxial deformation in the cross direction*
44. **Poisson's Ratio, v12 PE Patches -** *Describes the ratio from expansion in longitudinal direction to contraction in cross direction*
45. **Poisson's Ratio, v21 PE Patches -** *Describes the ratio from contraction in longitudinal direction to expansion in cross direction*
46. **PE Patch dimensions (Length x Width in mm) -** *The generated energy is dependent on the size of the patches and the strain on them. Defines the possibility of a patch with maximum dimensions of 85x85mm*
47. **Capacitance (85x85mm Patch) –** *Total capacitance that a patch of these dimension has*
48. **Open Circuit Voltage V_{OC} –** *Electrical potential of the patch with no external load connected to it*
49. **Short Circuit Current I_{SC} –** *Current flowing through the patch when the voltage across it is null (when the patch is short circuited)*
50. **Voltage at max. Power V_{mp} –** *Voltage generated when connected to a load and operating at its peak performance (maximum power output)*
51. **Current at max Power I_{mp} –** *Current flowing when connected to a load and operating at its peak performance (maximum power output)*
52. **Max. Power P_{max} –** *Maximum possible power that the patch can achieve*
53. **TEG Patch dimensions –** *The generated energy is dependent on the size of the patches and the strain on them. Defines the possibility of a patch with maximum dimensions of 85x85mm*

54. **Power consumption during sleep (µW) - MCU Conditioner -** *Defined by the current and voltage it operates by, it defines the "passive" power-loss when there is no measurement taking place -> How much time the system has before running out of energy*
55. **Power consumption active mode (µW) – MCU -** *Defines the input power needed, coming from the TPEG & supercapacitor. This also serves as a measurement to see how much time a measurement loop can last with a supercapacitor of defined dimensions*
56. **Energy consumption (%) conditioner vs. Input energy -** *How efficient is the conditioner energy-wise. This gives an estimate to the energy left to charge supercapacitor and feed all other components*
57. **Energy consumption (µWs) – FOS -** *How much energy is drawn from the supercapacitor during the sleep mode and during the measurement and data transmission mode. The ability to operate without temperature control is key. Lower power usage allows for more frequent measurements.*
58. **Data transmission distance (m) – WSN -** *Bluetooth LE and LoRaWAN transmission evaluated*
59. **Power consumption (µW/s) – WSN -** *Bluetooth LE transmission peak rate at <15mA*

60. **Systems resistance to UV light –** *Given that the system shall be mounted in the facade of a building, where exposure to UV waves is constant, a resistance to photodegradation is needed from the PEG and the EHS*
61. **System's resistance to chemical components of water and air in the environment –** *Given that the system shall be mounted on a building's facade, where exposure to weathering from water and air's components can take place, resistance to environmental chemical reactions is needed*
62. **Wind load resistance –** *The piezoelectric components will be installed and/or integrated in facade components with wind service load range as defined. The frequency generated should produce the energy needed by the purposes expected for facade use cases. The maximum wind load of the facade should not damage the PEG*
63. **IoT Platform –** *Design and deploy to collect all data in a structured way and communicate with BIM model for data visualization*
64. **Energy production and storage –** *Storage the energy from PZE and provide the energy for sensing and IoT platform guaranteeing the 24 hours function of facade use case (daily energy cycle)*
65. **Cost optimization –** *The facade can be energy supplied by cable, therefore a balance between InComEss system's components need to be validated for market utilization*

66. **Applied pressure on TEM during installation –** *Guarantee optimum pressure on module to maximize thermal exchange*
67. **Road vibration resistance –** *TEG performance resistance after complete Road Simulation Bench test*
68. **High adhesion stability against thermal stress –** *The TEG will be mounted on a surface which shall experience high temperatures at a constant rate. The mounting solution should firmly contact the TEG to the surface even at high temperatures*
69. **Flexibility / Integration / dimensions -** *The patch as well as the complete system will be integrated in a complex structure with limited space. In order to be bonded on the part, it would be of interest to have a flexible structure to follow the shape of the part. The dimensions shall be also limited to the available space and/or possibility to integrate it*
70. **Patch Thickness (mm) –** *Total thickness of finished patch to be mounted on a specified surface*
71. **Operational condition efficiency -** *Efficiency regarding operational conditions defined through the following: ~160°C = ΔT still to be tested, depending on placement location*
72. **Thermal fatigue resistance –** *TEG performance reduction after complete on bench thermal cycling*

73. **Thermal conductivity from the TPEG patch (W/(m*K)) –** *In order to have a significant temperature gradient between the cold and hot point without having an important heat flux, a relatively low conductivity is recommended.*
74. **Patch Thickness (mm) –** *Total thickness of finished patch to be mounted on a specified surface*

75. **Bonding materials' adhesive strength (N/mm²) –** *Adhesive strength should be defined, to avoid a rupture in the bonding layer due to occurring forces on the patch, leading to undesired separation from the plane structure*
76. **EMI from the TPE-EHS –** *Electromagnetic interferences coming from the electronic components from the TPE-EHS*
77. **Flexibility / Integration / dimensions –** *The patch as well as the complete system will be integrated in a complex structure with limited space. In order to be bonded on the part, it would be of interest to have a flexible structure to follow the shape of the part. The dimensions shall be also limited to the available space and/or possibility to integrate it*
78. **Standardized system -** *Same system to be adapted to metallic as well as composite structure - Possibility to integrate the system into composite structure during the composite part moulding (RTM or SQRTM or hand lay-up; 180°C curing cycle - material compatibility)*
79. **Respect of the requirements –** *A list of requirements is defined as part of deliverable D1.3 in order to assess/characterize TPEG material, TPEG system, Electronic board, bonding. It includes for example: Tg / Tm (thermoplastic) requirements, impact resistance, resistance to exposure to high/low temperature, humidity, water, slat spray, fluids, robust vibrations, single lap shear, peeling. See sheet "SONA requirements"*
80. **SHM –** *The system should be able to realize concrete measurement tasks that allow for a structural health monitoring to take place*
81. **Operational condition efficiency –** *efficiency regarding operational conditions defined through the following points:*

    TEG function: maximum ΔT= 50 to 70°C with intermittent actuation of the icing protection system (2 min at each switch-on; less than 10% of the flight duration in case of actuation);

    PEG function: random vibration at 5,0 Grms and from 0 to 367 Hz / 0 to 0,3 g²/Hz

    Operational conditions are explained as part of Deliverable 1.3 with associated proposed test conditions
82. **Durability –** *Measured through life cycles through mechanical stress, as well as thermal tests over time and temperature gradient changes*
83. **Maintenance cost/needs –** *Defines if the system needs maintenance or check-up and the time required between 2 checks. If the maintenance could be done using only an alert signal it could be an advantage. The maintenance assessment should also consider the cost to make the check and the reparation/replacement conditions. It is also linked to the risk analysis. If no risk for aircraft operation if the system failed between 2 general maintenance rounds, no big issue. If there is a risk (e.g. if no more SHM and a risk to not identified slat failure) on the aircraft operation, much effort shall take place to develop a robust solution*

7 Annex II. Data Gathering Protocol

7.1 Introduction

Environmental impacts have a significant economic dimension as they may play a decisive role for fostering industrial development. To mitigate environmental related effects to industrial activity, new strategies and technologies are developed focused on reducing, for example, emissions of CO2 and other gases connected to global climate change, local environmental problems relating to air quality and water pollution. In parallel, selection of raw materials is extremely important when Critical Raw Materials or Rare Earths Elements are involved in a productive process due to price volatility and regulations.

To quantify related effects of the introduction of a new process or technology in an industry, it is needed to incorporate methodological approaches based on environmental and economic assessments. To attain this aim, life cycle assessment and life cycle cost studies are generally applied to minimise environmental impact of processes while considering the associated costs. They are considered as useful tools to underline the importance of the best available alternative, because they offer the quantification of several indicators that have been defined to allow measuring different types of impacts.

Considering these two methodologies, the evaluation strategy planned to the InComEss project is based on an optimum environmental and economic performance assessment of the new materials and devices developed in the project along their whole life cycle. As a prerequisite of both methodologies, representative and reliable results should be provided based on the establishment of a correct data gathering protocol. In this vein, this document is aimed to offer guidelines to be carried out during the E-LCA/LCCA methodology applicability to the new InComEss technology.

7.2 Data gathering methodology

7.2.1 General description

To successfully apply the E-LCA and LCCA studies, the following actions should be considered to facilitate the data collection task:

- To determine (and create, if necessary) a method for collection, storage of data and retention of data.
- To identify potential data collection challenges and the precautionary measures to maintain the integrity of the study (e.g., incomplete surveys, lost permission forms, improper data entry).
- To monitor and support data collection activities.

The mentioned actions can be achieved by applying a reference working methodology aimed to assure that all the initial data required to carry out the proposed InComEss project goals are properly provided. To this end, a data gathering methodology has been structured into the main steps:

1. **Identification of data needs:** in order to detect information needed to perform the E-LCA/LCCA methodology, specific questions and doubts related to general data about the processes should be performed.
2. **Data gathering plan:** this step refers to the definition of the most proper collection tools, for instance, templates done in excel files. Format should be adapted to facilitate the task of gathering and processing data. Specific deadlines for providing support to collection activities and returning filled templates are also stablished in this step.
3. **Data collection and validation:** in this step collection tools are delivered, and data is gathered from different sources. It also implies both monitoring and supporting data collection activities to partners involved in this step. Then, gathered information is revised to detect possible gaps and/or inconsistencies in the information received. Finally, a refinement of collected data is carried out.
4. **Data analysis:** it consists on performing the E-LCA/LCCA methodology to obtain main results. By this step, the consistency of the results is verified, and data is validated. If missing or unknown data is identified, all steps previously described should be executed consecutively until no further information is needed.
5. **Sharing results:** main results and final conclusions of applying the E-LCA/LCCA methodology to the materials and devices developed in the InComEss project are shared as visual presentations or reports.

All the basic steps that comprise the data gathering protocol are summarized as shows Figure 7.1.

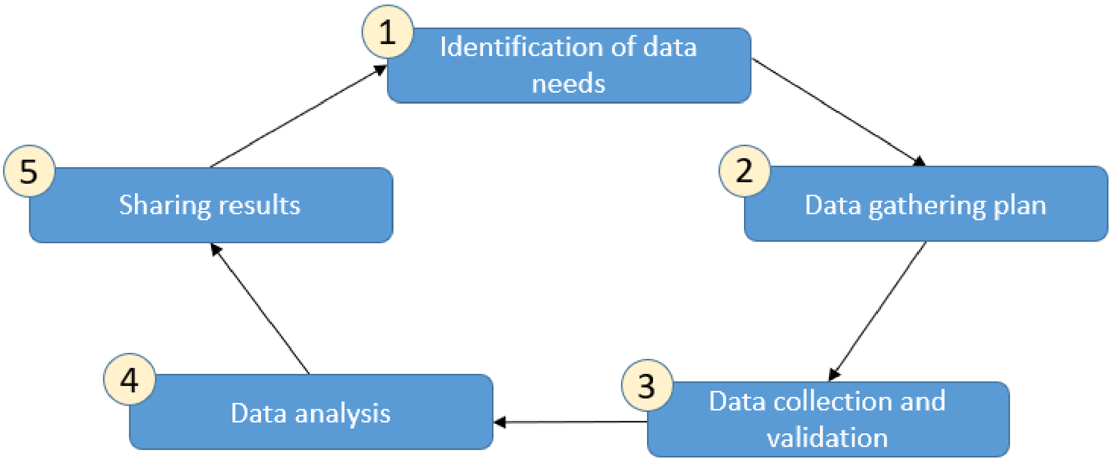


Figure 7.1: Steps of the Data Gathering Protocol

7.2.2 Identification of Data Needs

In this step, an initial study of the innovations involved in the InComEss project is performed in order to identify needs for data. To get knowledge about the processes, a full description of commercial products to create a baseline scenario to compare and a full description of new materials and devices should be provided by partners in charge of developing the new technologies involved in InComEss project.

Relevant information to be gathered implies the identification of inputs (materials and energy) and outputs (products, emissions, and wastes) as well as economic data needed to the LCC (costs related to acquisition, operation, maintenance and disposal). The most practical way to perform this step is to make a list of all the inputs and outputs related to the innovations under study by reviewing, for instance, flow charts of the processes. It will allow identifying main parameters of technological processes, which are required to develop E-LCA and LCCA studies (Task 8.3). In this step, different types of environmental and economic impact indicators will be selected and defined to each type of methodology considered (E-LCA/LCCA methodologies), based on the needs and concerns of the processes and framework of the project. Selected indicators will be further used to evaluate impacts related to the InComEss technology

Activities and resources:

- Identification of partner contacts, who are working on the processes involved in the InComEss project.
- Revision of the InComEss project technologies considering existing processes (baseline technologies) and new development.
- Contacting partners by different communication channels, for instance, on-line communication with partners via e-mail, videoconferences/teleconferences, intranet, SharePoint, phone calls or visits.
- Selection of target indicators based on literature and previous CIRCE's experience in E-LCA and LCCA carried out to similar technologies.

These activities will be performed as part of the Task 8.3.1 and 8.3.2.

7.2.3 Data gathering plan

Once a general revision of the processes (baseline and new technologies) has been already done, a data gathering plan starts by selecting and defining different communication channels to be used for the data gathering process. It comprises construction and validation of specific gathering information templates to be done by CIRCE, which may comprise charts and tables adapted to the InComEss processes. The generated templates (Excel Worksheets, surveys, etc.) will be sending to the corresponding project partners via e-mail. Deadlines for returning templates correctly filled will be notified in advance.

Activities and resources:

- Construction and validation of specific templates for the data gathering process.
- Distribution (via email) of templates to each specific partner.
- Establishment of deadlines for providing support to data collection activities and returning filled templates.

These activities will be performed as part of the Task 8.3.1 and 8.3.2.

7.2.4 Data collection and validation

This is a crucial step for a correct and reliable environmental and economic assessment. In this stage, information gathered by partners using the templates will be reviewed, validated and approved by CIRCE with the purpose of performing a collected data refinement.

Activities and resources:

- Scheduling video conferences/teleconferences, phone calls and / or other methods for achieving appropriate feedback of submitted data by partners.
- Clarification of doubts raised during the data gathering process considering different communication channels.

These activities will be performed as part of the Task 8.3.1 and 8.3.2.

7.2.5 Data analysis

In this step, data provided by partners is assessed to obtain main results. E-LCA and LCCA methodology will be applied to generate environmental, economic and dependence analysis of all the materials and devices involved in the new InComEss technology.

Activities and resources:

- Applying the LCA methodology considering CIRCE in-house databases and LCA software with specific databases.
- Applying the LCCA methodology based on collected data by partners and CIRCE calculation tools.
- Identifying critical and rare-earths materials demand and production for the sector and requirements for the innovations.

These activities will be performed as part of the Task 8.3.1 and 8.3.2.

7.2.6 Sharing Results

Presentation of deliverables with final conclusions attained by the E-LCA and LCCA methodologies is made for each of the assessed technologies included in the InComEss project. Confidentiality issues will be check with each involved partner before sharing the deliverables.

Activities and resources:

- Transferring results to partners via different communication channels, such as written and visual ones.

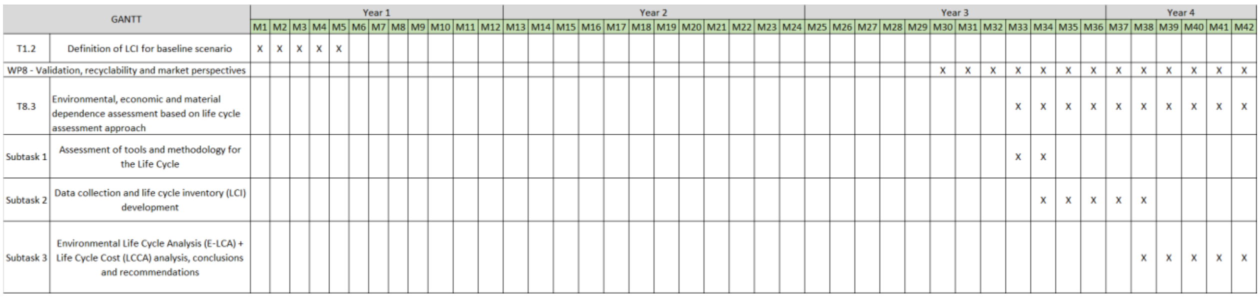
This activity will be performed as part of the Task 8.3.1 and 8.3.2.

7.3 Data gathering timeline for the InComEss project

This protocol will be used as guideline for guaranteeing the correct execution of Task 8.3 and therefore, timelines are planned according to the project Gantt. Based on this information as well as on the Task 8.3 definition, the following subtasks are specified:

- **Assessment of tools and methodology for the Life Cycle:** It corresponds to the definition of the life cycle methods and indicators to be used as reference for the evaluation of benefits implied by the new InComEss technology. As part of the gathering protocol - step 1, different types of target indicators will be selected and defined, considering the needs and concerns of the processes and framework of the project. Among expected indicators to be selected are factors such as: global warming, water consumption, ozone depletion, acidification and human toxicity.
- **Data collection and life cycle inventory (LCI) development:** In this subtask, the life cycle inventory is performed for the InComEss technology and for baseline scenario. It comprises steps 2 and 3 of the data gathering protocol, as it was specified in section 2.
- **Environmental Life Cycle Analysis (E-LCA) + Life Cycle Cost (LCCA) analysis, conclusions and recommendations:** It involves the development of the E-LCA/LCCA analysis of InComEss technology aimed to establish final conclusions and recommendations. Based on the data gathering protocol, execution of this subtask involves steps 4 and 5.

Execution of these subtasks is carried out between M1 to M5 (for the baseline scenario) and M33 to M42 of the project Gantt for the innovations. For each subtask, duration is planned as it is showed in the following figure:



GANTT		Year 1												Year 2												Year 3												Year 4					
		M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20	M21	M22	M23	M24	M25	M26	M27	M28	M29	M30	M31	M32	M33	M34	M35	M36	M37	M38	M39	M40	M41	M42
T1.2	Definition of LCI for baseline scenario	X	X	X	X	X																																					
WP8 - Validation, recyclability and market perspectives																															X	X	X	X	X	X	X	X	X	X	X	X	X
T8.3	Environmental, economic and material dependence assessment based on life cycle assessment approach																																	X	X	X	X	X	X	X	X	X	X
Subtask 1	Assessment of tools and methodology for the Life Cycle																																	X	X								
Subtask 2	Data collection and life cycle inventory (LCI) development																																		X	X	X	X	X				
Subtask 3	Environmental Life Cycle Analysis (E-LCA) + Life Cycle Cost (LCCA) analysis, conclusions and recommendations																																						X	X	X	X	X

Considering the Gantt steps to be followed according to the gathering data protocol are presented together with their expected timeline for the InComEss project in the following table:

Step	Timeline
Identification of Data Needs	M1-M3 and M33
Data gathering plan	M1-M3
Data collection and validation for baseline scenario	M3-M5
Data collection and validation for innovations	M33-M38
Data analysis of baseline and innovations	M33-M42
Sharing Results	M42 (Deliverable 8.3)

8 Annex III. Skeleton's ultracapacitors Life cycle inventory

The functional unit considered in this study is the manufacturing of one Ultracapacitor cell.

8.1 Electrode manufacturing stage

The first stage of the Ultracapacitor manufacturing process is the electrode production. The weight of one set of electrodes for one Ultracapacitor standard cell with 3200 F capacitance is 0.247 kg.

8.1.1 Inputs of electrode manufacturing stage

8.1.1.1 *Materials consumption*

The consumption of raw materials to manufacture the electrode for a standard Ultracapacitor cell is shown in Table 8.1.

Table 8.1: Material consumed to manufacture one electrode for one Ultracapacitor cell.

MATERIALS	UNITS	VALUE
Carbon	**Kg**	0.1852
Aluminium foil	**Kg**	0.1137

The following assumptions are made to carry out the environmental simulation:

- Carbon has been considered as activated carbon.
- The impact attributed to the transportation of raw materials from the supplier facilities to the Skeleton factory has been included in the analysis. The impacts have been calculated considering a maritime transport, in a transoceanic ship. The distance of each raw material is:
    - Carbon: 13,300 km.
    - Aluminium foil: 13,300 km.

8.1.1.2 *Other indirect consumptions*

Additionally, the energy consumption for the electrode manufacturing has been considered. This consumption is shown in Table 8.2.

Table 8.2: Energy consumption to manufacture one full electrode roll, being used to produce thousands of standard capacitors.

ENERGY	UNITS	VALUE
Electricity	kWh	72

- The European EU-28 energy mix has been used for the calculation of the impacts caused during the electricity generation.

8.1.2 Outputs of electrode manufacturing stage

The products obtained in this stage are included in Table 8.3:

Table 8.3: Products and by-products obtained in electrode manufacturing stage.

PRODUCTS/BY-PRODUCTS	UNITS	VALUE
Electrode	kg	0.247
Scraps	kg	0.0519

8.2 Cell assembly stage

The second stage of the Ultracapacitor manufacturing process is the cell assembly. The weight of one cell is 0.532 kg.

8.2.1 Inputs of cell assembly stage

8.2.1.1 Materials consumption

The consumption of raw materials to assemble the cell is shown in Table 8.4.

Table 8.4: Material consumed to assemble one cell.

MATERIALS	UNITS	VALUE
Electrode	kg	0.247
Electrolyte	kg	0.19
Aluminium cell parts	kg	0.096
Cellulose separator	kg	0.019

The following assumptions are made to carry out the environmental simulation:

- An inorganic electrolyte (KOH) has been considered for the simulation in a first stage due to lack of organic electrolyte in the Ecoinvent 3.4 database. Additional literature review will be performed.
- The cellulose separator has been considered in a first stage as a conventional battery separator.
- The impact attributed to the transportation of raw materials from the supplier facilities to the Skeleton factory has been included in the analysis. The impacts have been calculated considering a terrestrial transport - in a truck EURO 4 (for the aluminium parts) and in train (for the organic electrolyte)- and considering a maritime transport, in a transoceanic ship for the cellulose separator. The distance of each raw material is:
  - Electrolyte: 12,200 km.
  - Aluminium cell parts: 690 km.
  - Cellulose separator: 13,300 km.

8.2.1.2 Other indirect consumptions

Additionally, the energy consumption for the electrode manufacturing has been considered. This consumption is shown in Table 8.5.

Table 8.5: Energy consumption to assemble one cell.

ENERGY	UNITS	VALUE
Electricity	kWh	0.35

- The European EU-28 energy mix has been used for the calculation of the impacts caused during the electricity generation.

8.2.2 Outputs of cell assembly stage

The products obtained in this stage are included in Table 8.6:

Table 8.6: Products and by-products obtained in cell assembly stage.

PRODUCTS/BY-PRODUCTS	UNITS	VALUE
Supercapacitor cell	kg	0.532
Scraps	kg	0.02

8.3 Packaging stage

The material necessary for the packaging of the cell are included in Table 8.7:

Table 8.7: Material for the cell packaging.

MATERIALS	UNITS	VALUE
Cardboard	kg	0.003

8.4 Transport to client stage

The final product is sent to different destinations with different types of transport. All this information is collected in Table 8.8.

Table 8.8: Information about transport to client.

DESTINATION	% of total	Distance (km)	Means of transport
Germany	20	150	Truck EURO 4
Europe	40	900	Train
Rest of the world	40	7,000	Ship