(Projects funded under the Call 2014 onwards must use this format)

LIFE Project Number

LIFE17 ENV/ES/000216

Mid-term / Final Report

Covering the project activities from 01/07/2018 to 31/07/2022

Reporting Date[1]

31/07/2022

LIFE PROJECT NAME or Acronym

BIOTAWEE

Data Project

Project location:	Spain
Project start date:	01/07/2018
Project end date:	31/12/2020 Extension **date:** 31/07/2022
Total budget:	932,381 €
EU contribution:	907,381 €
(%) of eligible costs:	60 %

Data Beneficiary

Name Beneficiary:	REYDESA RECYCLING, S.L.
Contact person:	Ms Itziar Marquez
Postal address:	C/ San Antolín, 16, Pol. Ind. Goiain. 01170. Legutiano. Spain
Telephone:	+945 46 50 90
E-mail:	imarquez@fundacioninatec.es
Project Website:	https://www.biotawee.com/en/

1 Include the reporting date as foreseen in part C2 of Annex II of the Grant Agreement

This table comprises an essential part of the report and should be filled in before submission

Please note that the evaluation of your report may only commence if the package complies with all the elements in this receivability check. The evaluation will be stopped if any obligatory elements are missing.

Package completeness and correctness check	
Obligatory elements	**✓ or N/A**
Technical report	
The correct latest template for the type of project (e.g. traditional) has been followed and all sections have been filled in, in English *In electronic version only*	✓
Index of deliverables with short description annexed, in English *In electronic version only*	✓
<u>Mid-term report</u>: Deliverables due in the reporting period (from project start) annexed <u>Final report</u>: Deliverables not already submitted with the MTR annexed including the Layman's report and after-LIFE plan Deliverables in language(s) other than English include a summary in English *In electronic version only*	✓
Financial report	
The reporting period in the financial report (consolidated financial statement **and** financial statement of each Individual Beneficiary) is the same as in the technical report with the exception of any terminated beneficiary for which the end period should be the date of the termination.	✓
Consolidated Financial Statement with all 5 forms duly filled in and signed and dated *Electronically Q-signed or if paper submission signed and dated originals* and in electronic version (pdfs of signed sheets + full Excel file)*	✓
Financial Statement(s) of the Coordinating Beneficiary, of each Associated Beneficiary and of each affiliate (if involved), with all forms duly filled in (signed and dated). The Financial Statement(s) of Beneficiaries with affiliate(s) include the total cost of each affiliate in 1 line per cost category. *In electronic version (pdfs of signed sheets + full Excel files) + in the case of the Final report the overall summary forms of each beneficiary electronically Q-signed or if paper submission, signed and dated originals**	✓
Amounts, names and other data (e.g. bank account) are correct and consistent with the Grant Agreement / across the different forms (e.g. figures from the individual statements are the same as those reported in the consolidated statement)	✓
Mid-term report (for all projects except IPs): the threshold for the second pre-financing payment has been reached	**N/A**
Beneficiary's certificate for Durable Goods included (if required, i.e. beneficiaries claiming 100% cost for durable goods) *Electronically Q-signed or if paper submission signed and dated originals* and in electronic version (pdfs of signed sheets)*	**N/A**
Certificate on financial statements (if required, i.e. for beneficiaries with EU contribution ≥750,000 € in the budget) *Electronically Q-signed or if paper submission signed original and in electronic version (pdf)*	**N/A**
Other checks	
Additional information / clarifications and supporting documents requested in previous letters from the Agency (unless already submitted or not yet due)	✓

In electronic version only	
This table, page 2 of the Mid-term / Final report, is completed - each tick box is filled in *In electronic version only*	✓

**signature by a legal or statutory representative of the beneficiary / affiliate concerned*

Instructions: Please refer to the General Conditions annexed to your grant agreement for the contractual requirements concerning a Mid-term/Final Report. Both Mid-term and Final Technical Reports shall report on progress from the project start-date. The Final Report must be submitted to the Agency no later than 3 months after the project end date. Please follow the reporting instructions concerning your technical report, deliverables and financial report that are described in the document Guidance on how to report on your LIFE 2014-2020 project, available on the LIFE website. Please check if you have the latest version of the guidance as it is regularly updated. Additional guidance concerning deliverables, including the layman's report and after-LIFE plan, are given at the end of this reporting template. Regarding the length of your report, try to adhere to the suggested number of pages while providing all the required information as described in the guidance per section within this template.

1. Table of contents

2. List of key-words and abbreviations

PCB: Printed Circuit Boards
WEEE: Waste Electric and Electronic Equipment
EEE: Electric and Electronic Equipment
KPI: Key Performance Indicator
GA: Grant Agreement
CRM: Critical Raw Materials
Au: Gold
Ag: Silver
Cu: Copper
Pt: Platinum
Mos: Microorganisms
GA: Graptolite Argillite
NMF: Non-metallic fraction
MSW: Municipal Solid Waste
PG: Phosphogypsum residue
BR: BAUXITE RESIDUE
LIBs: Lithium-ion batteries
PMC: Project Management Committee
FTO: freedom to operate
FU: functional unit
PMC: Project Management Committee
SDGs: Sustainable Development Goals

3. Executive Summary (maximum 2 pages)

Collection, treatment and recycling of WEEE is essential to improve the environmental management, contribute to a circular economy and enhance resource efficiency. In this way, the recycling of WEEE offers substantial opportunities in terms of making secondary raw materials available on the market. Hence, LIFE BIOTAWEE project wanted to demonstrate the possible recovery of valuable metals (mainly Cu, Ag and Au) from the NMF of PCB of WEEE by the application of bioleaching technology. Bioleaching uses direct metabolism or by-products of microbial processes to solubilize a metal sulfidic ore or waste into an aqueous solution.

The project focus was on the necessity of increasing recovery degree of PCB of WEEE, contributing also to reduce European dependence of some high-valued metals with very low EU supply (mainly Au but also Cu and Ag). Moreover, promoting the biotechnology in the recycling processes of PCBs as the future feasible methods which can achieve the recovery objectives, reducing processing cost, CO_2 eq. and waste generation respect to a hydrometallurgical process. The achievements of the project have been:
- *Reduce the volume of unused fractions of PCB.* From 1 Tn of PCBs, almost 40 % may be integrated in the NMF of PCB (impurities after the mechanical treatment and the suction dust of the process).
- *Reduction in hazardous effluents waste generation of 3.88 Tn/Tn PCB respect a complete hydrometallurgical process.* Bioleaching is more environmentally friendly comparing to the use of solvents needed in hydrometallurgy.
- *Reduce 45 % CO_2 eq compared with the hydrometallurgical process*.
- *Materials were recovered per Tn of PCB applying 2 aerobic bioleaching processes:* 182 Kg Cu, 0.24 Kg Ag and 0.021 Kg Au. This recovery may be improved due to the optimisation need for the recovery of precious metals. The recovery for Au is stated in 45% and for the Ag 1-4%. So, there is room for improvement.
- *Reduction of 38% in the processing cost respect the hydrometallurgical process.*

Initially, LIFE BIOTAWEE wanted to demonstrate the possible recovery of valuable metals by the application of an innovative more efficient 2-step bioleaching technology, combining aerobic and anaerobic treatment. During project progress, LIFE BIOTAWEE process changed the proposed bioleaching technology for 2 consecutive aerobic steps (the first one for base metals and the second one for precious metals) due to the weak performance of the anaerobic step with the NMF of PCBs. Meanwhile, the project has demonstrated the viability of this 2-step bioleaching technology (anaerobic + aerobic) but applicated to a different waste (suction dust obtained from the mechanical treatment).

As a fundamental aspect of the project, the consortium underpinned the replicability options of the technology with the satisfactory results achieved with the treatment of suction dust from the mechanical processes. The replicability was approved by means of the evaluation of the technological and economic possibilities in widening the usage of the innovative technology on other complex wastes in order to reduce the processing cost.

Not only takes into account technical aspects of the proposed solution, but environmental and socio-economical are key aspects too. In that sense, the determining deliverables were:
- Technical aspects, B.1.2 Bench scale and B.2.2 Semi-industrial scale technical reports
- Feasibility/future, B.3.2 Cost-effectiveness and B.3.3 Replicability and transferability.
- Environment aspects, C.1.3 LCA and D.1.6 Analysis of synergies with EU policies.

- Dissemination, D.1.4 Report on technical publications and D.1.7 Layman report.

The project started in July 2018 and the expected end date was December 2020. However, in October 2020, an amendment for the extension of the project was requested and final date for finishing the project was stated in July 2022. The amendment for the extension was necessary due to the delay in action B1. If no extension was agreed, the project would not have been done in a semi-industrial scale. The delay in action B1, has marked the whole project holding back technical results and important decision as the building of the semi-industrial pilot plant.

Covid situation was partially responsible for action B1 delay, and also had strong implications in dissemination actions (conferences, seminars) and in holding face-to-face meetings and in the planned trips.

LIFE BIOTAWEE project helps to achieve the recycling objectives set in the Directive 2012/19/EU, and is in line with the circular economy initiatives, at European and local level. Therefore, this project aims to contribute to reducing supply risk and mitigating significant price fluctuations. It is a priority to reduce external dependency on the supply of metals by innovating in recycling processes and optimizing the management of metal scrap. The project also supports the Directive 2000/76/EC related to Waste incineration, because avoids incineration of 300 t/year of PCBs, reduction hazardous effluents and waste generation.

Main barriers detected are relative to the European List of Waste, that is not specific enough to detect the CRM in the waste streams, or even the presence of PCBs, as there are classified in a generic classification with “components removed from WEEE”. But REYDESA is participating in a H2020 project to tackle this problem by increasing the traceability of the CRM since manufacturing, improving not only its recovery, as well the overall environmental performance of the equipment as a product. The recently approved POPs regulation could affect the recyclability of plastics recovered from WEEE, as bromine flame retardants are contained in this fraction, and also could entail more cost in the process of WEEE.

The future of LIFE BIOTAWEE process involves several possibilities. PCB management service within the recycling industry is not common. In cases where the recycling industry treats PCB fractions, the process usually begins with a mechanical treatment to recover the fractions with the highest economic value, but it generates a non-metallic fraction that is difficult to manage, such as the one used in the LIFE BIOTAWEE pilot. The LIFE BIOTAWEE service has been defined to recover metal content in difficult-to-treat waste after certain conditions (>17% Cu or >50ppm Au).

Apart from the proposed service, the process will be implemented in the recovery of Li by Reydesa through a new project as a part of replicability actions. BIOTATEC will continue developing further strategies for valorisation of e-waste with grant from Estonian Government and EU as well as raising additional capital. The aim is to further develop and improve the bioextraction technology of various metals from different types of e-waste. Additionally, it will be explored the possible ways to increase the overall value of e-waste leaching process through biosynthesis of metallic nanoparticles.

4. Introduction (maximum 2 pages)

Environmental problem/issue addressed
WEEE is a complex mixture of materials containing precious and special metals as well as potentially toxic substances like lead, mercury, cadmium and beryllium, that poses considerable environmental and health risks if it treated inadequately. Moreover, the production of modern electronics requires the use of scarce and expensive resources, for example, less than 1% of total gold worldwide is obtained from European natural resources around 10% is used for EEE production. According to the European Commission, WEEE is one of the fastest growing waste streams in the EU and less than 40% is recycled[2]. According to the most recent data, at the European level, the collection of WEEE increased by 47.6% in the period 2011-2019 (4.5 million tons collected in 2019), and its recycling and preparation for reuse increased from 2.6 to 3.6 million tons in the same time interval[3].

Outline the hypothesis to be demonstrated / verified by the project
The hypothesis BIOTAWEE wanted to demonstrate, was the possible recovery of valuable metals (mainly Cu, Ag and Au) from the NMF of PCB of WEEE by the application of an innovative more efficient 2-step bioleaching technology, combining aerobic and anaerobic treatment. During project progress, LIFE BIOTAWEE process changed the proposed bioleaching technology for 2 consecutive aerobic steps due to the weak performance of the anaerobic step with the NMF of PCBs. Meanwhile, the project has demonstrated the viability of this 2-step bioleaching technology (anaerobic + aerobic) but applicated to a different waste (suction dust obtained from the mechanical treatment (replicability).

Description of the technical / methodological solution
Bioleaching is a generic term for a biotechnical solution currently used for processing of metal containing ores and concentrates. The industry uses the microorganism's natural ability to digest, absorb and change the quality of different metals and chemicals to refine it. Compared to conventional metallurgy approaches, bioleaching is becoming more and more popular as a cheaper, more reliable, more efficient, safer and environmentally friendlier way to extract metals. In 2010, BIOTATEC performed trial bioleaching tests with Graptolite Argillite and due to fascinating results further investigation was carried out resulting a vision of a combined method for degradation of organics and bioleaching of metals from argillite. BIOTATEC developed a nature-based route 2- step technology (BiotaMet) that comprised both aerobic and anaerobic stages in stirred reactors, where methane gas was generated, and metals were bioleached. 5 years of long research resulted with submission of patent application in January 2016.

Despite this technology has been tested in natural sources and there is a lot of information at laboratory scale, there are not cost-effective methodologies at industrial scale, with production costs of less than 2.000 €/ton, that can be implemented to the recycling of PCB of WEEE. The implementation of this technology involves improving the cost-effectiveness of hydrometallurgical processes estimated in 3,846 €/Tn.

[2] https://www.europarl.europa.eu/news/en/headlines/society/20201208STO93325/e-waste-in-the-eu-facts-and-figures-infographic (26/04/2022).
[3] https://ec.europa.eu/eurostat/statisticsexplained/index.php?title=Waste_statistics_-_electrical_and_electronic_equipment#Electronic_equipment_.28EEE.29_put_on_the_market_and_WEEE_collected_by_country

Expected results and environmental benefits

LIFE BIOTAWEE aimed to increase the total efficiency of recycling the PCB of WEEE via adding environmentally friendly approach to the cycle. Waste residue from current recycling process contains plastics and a considerable number of valuable metals that are not extractable from the non-metallic residue with common traditional processes. Maximum number of valuable base metals were extracted at semi-industrial scale and an approach for Au extraction was proven at 20L. Furthermore, the replicability and transferability of the technology variants were tested achieving viable processes, both for NMF of PCBs as for suction dust or other interesting wastes as managing of LIBs.

- Reduction in hazardous waste generation of 0.3 Tn at the end of the project respect a complete hydrometallurgical process. 4.68 Tn waste (solid + effluents) was reduced in 2 aerobic bioleaching.

- Reduction 1,035 kWh electricity consumption respect hydrometallurgical processes at the end of the project. This reduction was based in the impact of the generation of CH_4 in the global consumption of the process. Since the generation of CH_4 in the anaerobic phase for the treatment of NMF of PCBs was not satisfactory, this reduction was not possible. The electricity consumption in 2-aerobic steps was 2,477 kWh vs hydrometallurgy 331 kWh.

- Reduction 0.8 Tn CO_2 emission respect hydrometallurgical processes at the end of the project. The reduction of CO_2 emissions respect hydrometallurgy is 0.76 Tn CO_2 eq, so was practically achieved (2-step aerobic bioleaching: 1052 Kg CO2 eq vs hydrometallurgy: 1850 Kg CO2 eq).

- Reduction 35-40% processing cost respect 1-step bioleaching processes. Final LIFE-BIOTAWEE process is based on 1 step aerobic bioleaching process to extract base metals, mainly Cu, and can be completed adding a second step aerobic bioleaching process to extract precious metals. The estimation for reduction was based on BIOTATEC's knowledge from methane production given for 2-step bioleaching (anaerobic + aerobic). It was estimated that the methane generation will provide a reduction of 40 % in costs = 0.5€/Kg. After the project, the proposed treatment for the NMF of PCB using the anaerobic phase is not efficient due to non-satisfactory generation of CH_4.

- Reduction 50% processing cost respect a complete hydrometallurgical process. The reduction obtained is 38 % respect the hydrometallurgical process. The bioleaching process carried out in LIFE-BIOTAWEE project has been a selective process. For this reason, two bioleaching stages have been defined with two different types of bacteria (to extract the Cu. Fe and Al content and to extract the Au content). The hydrometallurgical process was estimated in 3,846 €/Tn and the 2-step bioleaching process was 2,372 €/Tn.

5. Administrative part (expected 1 page)

To assure a smooth management it has been created the Project Management Plan which details the contents and structure of the project as well as the management procedure, general rules for justification, beneficiary financial statements, final audit, payment procedure, document management and project change procedure and potential problems.
(Deliverable LIFE_BIOTAWEE_E.1.2. Management Plan)

In mentioned management plan, the organisational structure of the project Consortium was defined. And it is shown in the following figure:

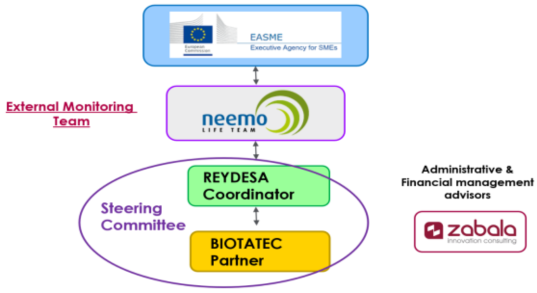


Figure 1. Organisational structure of LIFE BIOTAWEE project

The Project Coordinator is the legal entity acting as the intermediary between the Parties and the Funding Authority. The Project Coordinator shall, in addition to its responsibilities as a Party, perform the tasks assigned to it as described in the Grant Agreement and the Partnership Agreement.
Action Leaders: Each Action has a leader in charge of the coordination of the tasks. So, for each action, its leader and time frame were defined and updated during the project.

ACTIONS	LEADER	PATICIPANT
A1	BIOTATEC	REYDESA
B1	BIOTATEC	REYDESA
B2	REYDESA	BIOTATEC
B3	REYDESA	BIOTATEC
C1	REYDESA	BIOTATEC
C2	REYDESA	BIOTATEC
D1	REYDESA	BIOTATEC
E1	REYDESA	BIOTATEC

Figure 2. Action Leaders

Changes due to amendments to the Grant Agreement: Forms A1, C2 and C3.
Furthermore, the duration of the project in Art. I.2.2 of the grant agreement is extended and shall run from 01/07/2018 to 31/07/2022.

TIMETABLE

Action		2018				2019				2020				2021				2022			
Action numbe	Name of the action	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV
A. Preparatory actions (if needed)																					
A.1	Feasibility study			■	■																
B. Implementation actions (obligatory)																					
B.1	Optimisation of bioleaching process				■	■	■	■	■	■	■	■	■								
B.2	Pilot building and operation			■	■	■	■	■	■	■	■	■	■	■	■	■	■				
B.3	Post-processing													■	■	■	■	■	■	■	
C. Monitoring of the impact of the project actions (obligatory)																					
C.1	Monitoring of the environmental impact of the project						■	■	■	■	■	■	■	■	■	■	■	■	■	■	
C.2	Monitoring of the socio-economic impact of the project									■	■	■	■	■	■	■	■	■	■	■	
D. Public awareness and dissemination of results (obligatory)																					
D.1	Dissemination and public awareness			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	
E. Project management (obligatory)																					
E.1	Project management			■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	

Figure 3.Updated LIFE BIOTAWEE timetable

6. Technical part (expected 25 pages)

6.1. Technical progress, per Action

A1: FEASIBILITY STUDY
Foreseen start date: July 2018 Actual start date: July 2018
Foreseen end date: October 2018 Actual (or anticipated) end date: October 2018

Activities undertaken and outputs achieved
The applicability of consortium ARGCON5 for the use with PCB-s of WEEE was proved, and it was concluded that it was possible to enrich a methane producing microbial community from e-waste from Reydesa (PCB-s of WEEE, fraction F15).
Although the initial methane yield and metals extraction ability were modest, they can be improved in further steps with modifying the medium and by means of adaptive laboratory evolution (action B1 Biotatec) and experimental conditions (action B2 Reydesa-Inatec)
Deviations and main problems:
The composition of the non-metallic fraction of PCB is lower than the expected in precious metals (Au and Ag) and no content of Pd was detected. This may hinder the bioleaching and the recovery of the precious metals. The detected differences are due to the original nature of PCBs. Current PCBs have lower content in precious metals than the traditional ones.

Deliverable Name	Deadline	Achieved (Yes/No)
A.1.1 Feasibility expected report	October 2018	YES
Milestone Name	Deadline	Achieved (Yes/No)
A.1.1 Characterization of specific waste from REYDESA	August 2018	YES
A.1.2 Mediums and conditions selected both for biodegradation of the organic matter and for bioleaching of extracting valuable metal compounds	October 2018	YES

B1: OPTIMISATION OF BIOLEACHING PROCESS
Foreseen start date: October 2018 Actual start date: October 2018
Foreseen end date: June 2019 Actual (or anticipated) end date: October 2020

Activities undertaken and outputs achieved
Main objective of action B1 is to carry out various bioleaching tests with conditions and waste stream selected in Action A1 in order to perform bench scale tests at 20 L. Both lab scale tests and bench scale tests were separated into different phases: anaerobic phase and aerobic phase.

Lab scale phase (250 ml-1L):

Phase 1: Anaerobic cultivation experiments
The experiments were performed to simulate the process in anaerobic fermentation reactor.
The following tasks were carried out during the optimisation process:
- *Study of microbial biodegradation potential* of indigenous species of ARGCON5 and typical microbial community used in bioleaching metals in anaerobic conditions; cultivation experiments in microcosms.
    - Testing the microorganisms on the use of waste streams of recycling WEEE as carbon and energy source with defined media. R2A and vinasse was used, the use of porphyrins as model compounds of biodegradation process is inappropriate with e-waste; they could be used only in the case of certain minerals (shales).
- *Optimization of cultivation conditions and media* in waste streams microcosms to enhance microbiological degradation of organics
    - To study of composition of indigenous strains: isolation and characterization of culturable indigenous strains aiming at optimizing the degradation of organics with mixture of selected isolated strain were done.
- *Functional studies of the microbial community* with organics degrading ability (GC, δ 13C-CH4, δ 13CCO2of gas phase; metabolites (C-, S-, N-compounds, metals) in liquid and solid phases, drafting the mass balance through GC analysis were done.
- *Statistical and bioinformatic analysis*; sequencing the whole genomes of most important potent organics degrading/metal releasing strains completed; models for sulfur and nitrogen metabolism proposed;

The aim of the experiments was to compare metal leaching from the e-waste sample from Reydesa (PCBs of WEEE):
1) with inoculum ARGCON5 (inoculum 5A) vs inoculum 32 (an e-waste-adapted community);
2) with medium (+ inoculum) vs e-waste solution (+ inoculum);
3) with e-waste solution (+ inoculum) vs without inoculum;
5) with culture media (R2A broth and vinasse) vs sterilized tap water;
6) compare different media components – betaine vs vinass.

Finally, using 1.5 g of PCB-s of WEEE (fraction F15 INITIAL) as a substrate within 120 days 71.95 ml of gas per g e-waste was released with methane content 23 to 50% (medium R2A + ARGCON5 + 1% e-waste).

Phase 2: Aerobic cultivation experiments

With the help of pure culture of *Acidithiobacillus ferrooxidans* DSM14882 it was possible to release <10% Fe, 80% Ni, and 60% Cu from the residue NMF originating from the anaerobic phase within 48 hours. For some metals (Cu, Zn) the leaching efficiency was almost the same as with untreated NMF, except for Ni. Fe is needed as reactant in acidophilic process, so it is therefore also consumed during the process.

Au and Ag was not released. Release of Au is feasible with cyanogenic pure cultures, e.g. Chromobacterium violaceum. And Pseudomonas . However, release of Ag is feasible with At. Ferrooxidans, At. Thiooxidans, Thiobacillus denitrificans,Thiobacillus thioparus, Bacillus subtilis, Bacillus cereus, but the current experiments did not give satisfactory results.

Experiments with aim to neutralize the remaining waste:
To be able to perform further experiments with material from *A. ferroxidans* leaching, neutralization of material was carried out.
Results:

- It takes 160 mmol of NaOH to neutralize 1L of leachate.
- As a cost-efficient alternative, we explored the capacity of oil shale ash from Estonian electricity plants to neutralize leachate. It will take 100 grams to bring pH of 1 L leachate to 6,75.
- Neutralization of WEEE after acidophilic leaching requires 290 nmol of NaOH per 1 gram of solid material.

Bench scale phase (20L):
In this task 4 experiments were performed using NMF of PCB: three complete (phase anaerobic + phase aerobic) and another one only based on anaerobic phase. The aim of this task was:
1. Scale up the process to 20L,
2. Confirm the conclusions obtained in lab scale experiment related to methane generation with NMF of PCB,
3. Optimise the aerobic microorganisms to release base metals and precious metals.

<u>Performed experiments:</u>
Experiment 1: compares pre-treated NMF of PCBs (F15 Initial) from anaerobic bioleaching experiment (ARGCON5) vs untreated NMF of PCBs (F15 Initial) using Acidithiobacillus ferrooxidans in aerobic phase (to release base metals)
Experiment 2: Runs pre-treated NMF of PCBs (F15 Initial) from anaerobic bioleaching experiment (ARGCON5).
Experiment 3: compares pre-treated WPCBs (F5 1ª Vuelta sample 3) from anaerobic bioleaching experiment (ARGCON5) vs untreated WPCBs (F5 1ª Vuelta sample 3) using a mixed culture of Acidithiobacillus ferrooxidans and Acidithiobacillus thiooxidans in aerobic phase (to release base metals).
Experiment 4: compares pre-treated WPCBs (F5 1ª Vuelta sample 3) from acidophilic bioleaching experiment vs untreated WPCBs (F5 1ª Vuelta sample 3) using Chromobacterium violaceum culture in aerobic phase (to release precious metals).

The overall conclusions from this bench scale phase were:
• The functionality and reliable joint operation of various parts of the bench scale reactor (20 L) was tested in 4 anaerobic and 3 aerobic experiments.
• The reasons for misfunctioning of reactors (interruption in data acquisition, weak inoculum, small inoculum volume, clogging of gas filter) were elucidated and fixed;
• *Methane generation:*

  • As the main value of the anaerobic step is generation of biogas, attention should be paid to the proper choice of inoculum viability and concentration.
  • pH is an important parameter to follow the kinetics of the bioleaching process and a reliable indicator on the possibility of methane generation.

• From the experiments performed, the methane generation was not possible using non-metallic fraction of PCB (experiment 1 and 2). This issue, apart from the optimization needs, may be due to the nature of the waste. Non-metallic fraction of PCB is an heterogenous material with a bigger particle size than other materials where the 2-step bioleaching process had achieved better results. In order to have a deeper knowledge a 2-step bioleaching process was performed with another waste (filter dust, more homogeneous and with a reduced particle size) and the biogas generation in the anaerobic step with 1% suspension of zig-zag filter dust in the 20 L reactor was confirmed (62% CH_4 in gas phase).

• *Cu extraction using aerobic At. Ferrooxidans:*

• In the experiment 1 aerobic phase was conducted using At. Ferrooxidans. The extraction of Cu using the 2-step anaerobic-aerobic process was almost twice more efficient than using the aerobic process only. However, these results should be considered as very preliminary and not yet not reliable due to inaccuracy of the process. The extraction yield of copper for the tests performed in 250 ml was lower than in the previous test also due to the quality of inoculum, 28% vs 60% (deliverable B.1.1).

• *Cu extraction using aerobic Acidithiobacillus ferrooxidans and Acidithiobacillus thiooxidans:*

• In the experiment 3 aerobic phase was conducted using Acidithiobacillus ferrooxidans and Acidithiobacillus thiooxidans. The extraction of Cu using the Acidophilic bioleaching was more efficient with untreated wastes (84%) compared to anaerobically pre-treated residue (62%).

• *Ag and Au extraction using aerobic Chromobacterium violaceum:*

• In the experiment 4 aerobic phase was conducted using Chromobacterium violaceum. In the presence of cyanide Al, Cu, Cr, Pd and Au form cyanides complexes which show water solubility. Almost 45% of Au was released in the initial stages using untreated material vs a 14% of Au released using anaerobically pre-treated material. However, dicyanoaurate does not remain stable in solution with prolonged incubation times, that might be due to sorption processes onto biomass or biodegradation because metal cyanides serve as carbon or nitrogen source. So, further optimization should be done before scaling up the process.

<u>Deviations and main problems:</u>
During this process several problems happened. Mainly economical ant technical problems that has directly impacted in technical works carried out. During the project, BIOTATEC has faced economic problems. The majority of BIOTATEC costs were planned to be generated during the first 12 months of the project, creating a lack of working capital as it was informed in Midterm report. Also, there was a delay due to Covid situation in 2020 and BIOTATEC faced problems to hire qualified personnel.

In relation to technical the following problems and consequently deviations took place:

- Misfunctioning of reactors (interruption in data acquisition, weak inoculum, small inoculum volume, clogging of gas filter) were elucidated and fixed.
- The adaption period of microbial consortia for extracting Au and Ag from e-waste has been longer than anticipated. Although consortia were adapted successfully to extract Cu, however adaption of microbial consortia to extract Ag and Au was not satisfactory.

Besides the extension of the action B1 until October 2020, conclusions from experiments 3 and 4 arrived when the action was already finished.

Deliverable Name	Deadline	Achieved (Yes/No)
B.1.1 Lab scale technical report	March 2019	YES
B.1.2 Bench scale technical report	October 2020	YES
Milestone Name	**Deadline**	**Achieved (Yes/No)**
B.1.1 Anaerobic cultivation methodology at lab scale (250ml-1L)	December 2018	YES
B.1.2 Aerobic cultivation methodology at lab scale (250ml)	March 2019	YES
B.1.3 2-step bioleaching process methodology at bench scale (20L)	October 2020	YES

B2: PILOT BUILDING AND OPERATION

Foreseen start date: June 2019 Actual start date: July 2018
Foreseen end date: August 2020 Actual (or anticipated) end date: October 2021 (May 2022)

Activities undertaken and outputs achieved

This action comprised 3 tasks:

- B.2.1. Supply/sample preparation (*B.2.2 Semi-industrial scale technical report*)
- B.2.2. Pilot building and installation (*B.2.1 Installation report)*
- B.2.3. Set-up and operation. (*B.2.2 Semi-industrial scale technical report*)

B.2.1. Supply/sample preparation: (Reydesa)

A deep analysis was done on what PCB are, its composition, PCBs waste management, recycling technologies of PCBs (physical and chemical recycling), and industrial application of PCB recycling. (*Deliverable B.2.2*). To highlight, due its importance to the project, the grades of PCBs. In PCB waste management practice, the PCB waste is categorized into three groups (A/1, B/2, C/3) based on precious metals concentrations. This categorization is not a strictly defined selection system, but it is commonly used in WEEE management systems. BIOTAWEE project was focused in the treatment of PCBs grade 1 and 3. However, in order to obtain enough number of PCBs, purchase actions were carried out by the Plant Director from the beginning of the project for all kind of grades. These purchases were made by evaluating the monthly amounts that the usual PCB provider has in stock and the categorization was made by price (taking into account the precious content by EEE product).

Obtained PCB. The total amount of PCBs treated were 27,51 Tn, including PCBs grade 1 and 3, in order to test the technology with the current range of waste that it presents in the market. The inclusion of the PCBs grade 3 fulfil two objectives: the first one, was the necessity of optimisation of the mechanical treatment, steps 1-2. In these two steps there is a huge loss of material and is very important to have a perfect control of the suctions in order to decrease the precious metals loss. For this purpose, preliminary tests were done to achieve the best conditions in the process with several tones of PCBs grade 3 (9.14 t). The second objective was to take advantage of the opportunity to test the bioleaching technology on a wider range testing the effectivity with a lower precious metal content. These tests were useful to identify the viability of the process. PCBs grade 3 are an important waste flow that needs to be taken into account. To highlight, the composition of the NMF of PCB obtained is lower in precious metals and Cu than the expected one. This was found in both grades, and can be related to the metallic content on current PCB which is lower, especially in precious metals compared to the PCB manufactured some decades ago.

Processing PCBs. Processing PCBs includes several steps of crushing and separation until there was obtained a NMF to test by bioleaching technology. Next figure shows the material through each step of the process until the final fraction is achieved. The process finally performed was slightly different from the process proposed at the proposal. The changes were done by the new team with the aim of improving the efficiency in the new mill used in the process. Once the mechanical process was optimised, the rest of the material was processed. An example of each step of the process in *Deliverable B.2.2* can be found. Filter dust zig-zag from step 2 was used to study the application possibilities in *Replicability task B.3.2 and deliverable B.3.3.*

Figure 4 .Material through each step of the process.

Processing another WEEE material for replicability test. In order to perform replicability tests, suction dust from mechanical treatment was selected. This suction dust is generated at different points in the processing of WEEE, and depending on the material being processed, its composition may vary. In general, it can be said that this waste has metallic contents that tend to be between 10 and 30%, mainly Cu, and in some cases Fe, corresponding the rest of the material to NMF of low granulometry. Some particular filters are considered dangerous wastes due to its Pb content (> 0.3%); being difficult to treat, due to its fine granulometry and content of organic matter (20-30%) and inert (35%). Processes capable of treating fragmentation fines are not known in a European scale. Currently, the only commercial destination is Germany to be treated in large furnaces of waste management refineries, provided that the metal content is high and also subjected to the interests of the final manager. For this purpose, 7,42 Tn of WEEE were treated and suction dust was treated by aerobic bioleaching, the obtained results for Cu extraction were similar to the treatment of NMF of PCBs (*more info section B.3.2 and deliverable B3.3).*

B.2.2. Pilot building and installation (Reydesa-Inatec)

The development of a 50 L prototype for bioleaching operations of the non-metallic fraction of PCBs after mechanical treatment by the microorganisms Acidithiobacillus ferroxidans was carried out. The pilot plant was redesigned from 200-300 L to a reactor of 50 L because the consortium thought that a better control of the process was necessary after the preliminary results in 250 ml experiments given by BIOTATEC and this control would be achieved reducing the scale up and using 50 L is considered appropriate to give enough information to build a future industrial line. The modifications related to the pilot plant were exposed in the Mid-Term report and approved after sending additional information in May 2020. In the following figure, the pilot plant with all the components needed for the aerobic bioleaching is shown:

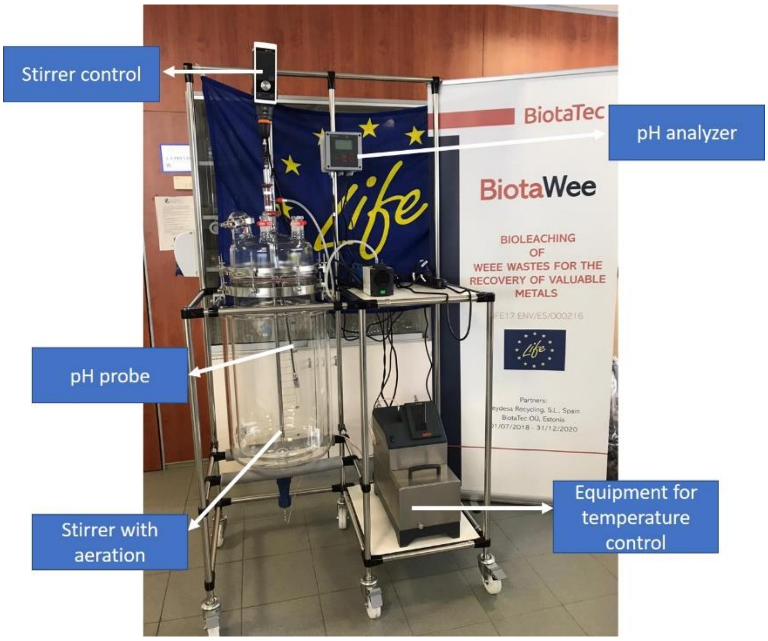


Figure 5. Pilot plant built for BIOTAWEE project.

A detailed description in *B.2.1 Installation report.*
The pilot plant consists on the following equipment to control the operating conditions during bioleaching:
- pH analyser that will facilitate both the supervision of the evolution of the pH of the reaction and also the possibility to set the pH at a constant value.
- Stirring controller + aerated rod for controlled agitation that does not hinder the evolution of microorganisms and also incorporates aeration in the rod to improve air recirculation for the benefit of the aerobic reactions that take place.
- T controller that allows us a precise control which is of great importance for the reactions and survival of microorganisms.

B.2.3. Set-up and operation (Inatec-Reydesa)
The main objective of this action is to treat the NMF of PCB obtained in task B.2.1. with the bioleaching technology in aerobic stage at a semi-industrial scale at 50L through the operation of batches. *Deliverable B.2.2* includes the preparatory actions required for doing so, a description of analysis to be performed in the tests, and finally, the results obtained in these tests.

Different tests in lab scale were performed in order to optimise the conditions for the scale up:
- pH 2: starting at pH 2.
- Fe 9 g/L: Increase [Fe] using 9 g/L instead of 4 g/L
- pH 2 + Fe 9 g/L: Increase [Fe] and starting at pH 2.
- pH constant: controlling the pH and maintaining it at 2.
- Adaptation steps to 10 g PCB/L

It was concluded that with pH adjusted, the [Fe] remains constant and the yield increase, achieving more leaching in less time. The optimal adaptation steps are: 1.5, 2.5, 5, 7.5, and 10 g PCB/L. The heterogeneity of the waste has been demonstrated by the analysis (replicated 20 times) of acid leaching with 2 gr of initial sample. More accurate results are obtained with analysis performed with 20gr of this waste, that is being used in the calculations. In Figure 6an scheme of the adaptation process of the microorganisms to a bigger volume and the presence of the pre-treated NMF obtained from the mechanical treatment of PCB is shown.

The test in 50 L that have been performed are the following:

- Test 1: This test is performed in 10 g/L with the bacteria that have been adapted to the NMF of PCB without pH control. It comes from the adaptation steps evaluation, and the bacteria that showed the best results (those adapted with the slightly modified conditions) were selected to tests in larger volume.
- Test 2 y 3: These tests are performed in 10 g/L with the bacteria that have been adapted since the beginning with the optimized conditions. That means controlling the pH, and with the optimized adaptation steps (slightly modified conditions). In this case, two replicas have been performed in order to evaluate the robustness of the results.
- Test 4: This test is performed in a higher percentage of solid, 70 g/L, with the aim of evaluating the potential increase of ratio solid/ liquid to increase the viability of this process. The bacteria used in this test were adapted without controlling pH, with slightly modified conditions in the adaptation, but when reaching 10g/L, the increase was the following: 12.5, 20, 30, 40, 50, 60 and 70 g/L. In these adaptation steps, the pH had to be controlled in order to get viable tests to proceed with the adaptation.

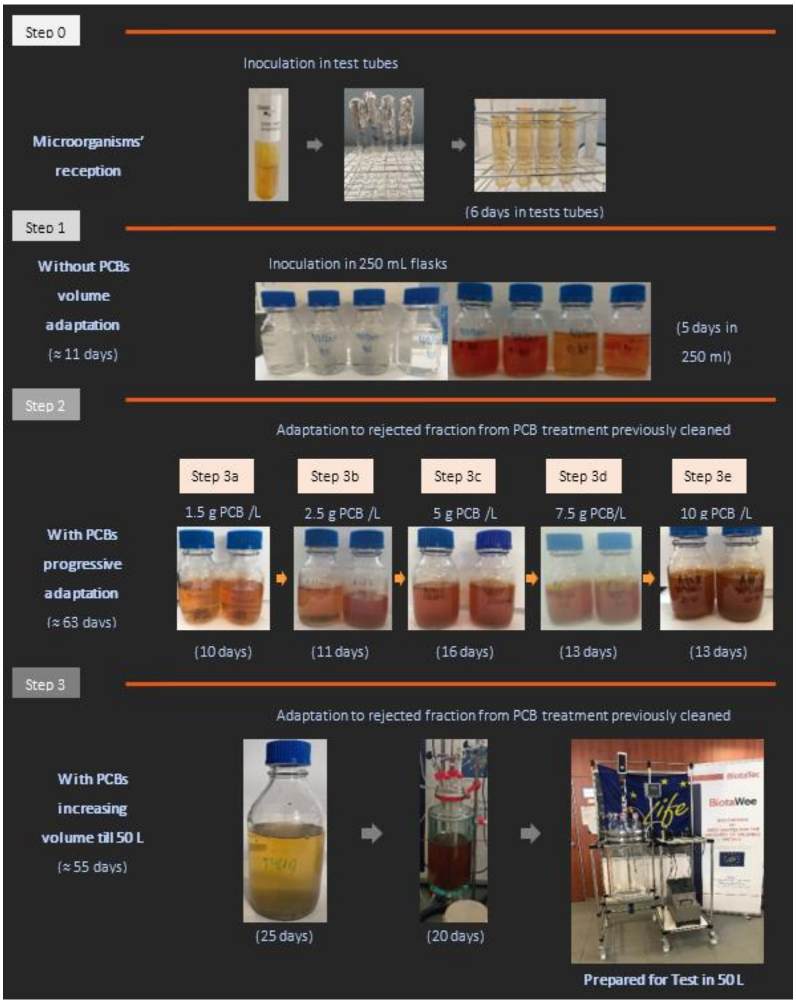


Figure 6. Scheme of the adaptation process of the microorganisms to a bigger volume and the presence of the pre-treated non-metallic fraction obtained from the mechanical treatment of PCB.

Conclusions of test performed in 50L only with the aerobic phase, showed a recovery of 86 – 95% Cu and 1-4% Ag. Other metals contained in the waste in very low quantity have been also extracted with a recovery, around 76-88.5 % Al, 98% Zn or 53- 55% Ni.
It can be concluded that gold is not recovered by applying bioleaching with A. ferroxidans.
In the case of Pt, analysis of the initial sample showed that its content is lower than 0.0005% of Pt in the NMF of PCB, and it is considered under the limit of detection and for this reason as non-contained in this waste.
The adaptation steps were performed to increase the PCB content, and it was observed that time for adaptation is higher than expected (>30 days), and pH adjustment was highly required to facilitate adaptation. There are survival problems with more than 7% PCB, and also when performing test in bigger volumes. The maximum increasement obtained inside BIOTAWEE project was with 6 % PCB. It can be concluded that currently the increase of PCB in this test to reach 7% is not feasible, and more adaptation and more analysis would be required in order to increase the volume.

<u>Deviations and main problems:</u>
During this process several problems happened. As it was commented in action B1, BIOTATEC faced economical ant technical problems that has directly impacted in technical works carried out. The delay in action B1 highly impacted in action B2 due to the present action should have been the semi-industrial implementation of a method developed in action B1. Preliminary data from the experiments in 250 ml were obtained in Mid-term report. The results showed almost the same results for the metal extraction using 1 step aerobic bioleaching than using 2-step (anaerobic + aerobic), so the consortium made the decision about not implement this anaerobic step in the scale up. It was found that the main use of the anaerobic step is the methane production, however at the moment of the Mid-term report there was not enough data that guaranteed a correct production of methane, because at small scale the gas production was minimum (using 1.5 g of PCBs as a substrate within 120 days gives 72 ml of gas per g of PCB with a methane content between 23 to 47 %. This means a yield calculated in the highest range, in optimized conditions at laboratory scale of 3.7 % to 7.0%). Finally, after the action B1 was finished, obtained results in 20L experiments using 2-step bioleaching (anaerobic + aerobic) using the NMF of PCB performed by BIOTATEC demonstrate no evidence of proper gas production and showed that further optimisation was needed for the treatment of NMF of PCB.

So, after those delays and the various stages of redesign, a final semi-industrial pilot plant of 50L for aerobic bioleaching was implemented in INATEC's laboratory. As it was mentioned before in the Mid-term report, in the grant agreement, the activities related to the bioleaching process (B2.3 Set-up and operation) and post-processing (B3.1 metal extraction from pregnant solutions) and the lab task inside B3.2. related with the transferability of the process using another waste stream, were done in the facilities of INATEC instead of in REYDESA's plant. This change obeyed to the difficulty founded by the consortium in the technical working operations of the bioleaching process and the conditions needed for the reactions. The process was better controlled in the laboratory area than in the designated area in the plant. Also, it has to be taken into account, that experts decided to change the material of bioreactor from steel to glass and decrease the volume to 50 L to have a better control of the reactions performed. The consortium selected to address these stages in the chemical lab in INATEC, performed by the laboratory technicians and the supervision of the researchers and the innovation manager. To sum up, to tackle these technical challenges a conversion of the number of hours set for REYDESA in action B2 were performed by INATEC as it was thought a better way to cope the objectives presented.

Deviations focused on pilot building and installation:
The new design of the planned pilot plant was expected to be launched to providers in March 2020 and was expected to have it by the summer, along with the final results of action B1 in the 20 L reactors by BIOTATEC. However, the COVID-19 situation forced us to delay this task until the last week of June 2020. The Spanish government declared the state of alarm on 14th of March and REYDESA-INATEC'S workers were advised to work from home as much as they can. The government extend the state of alarm until 12th of April, reducing the companies allowed to continue with their activity only to the ones that may considered inside essential activities as is compiled in RD – Ley 10/2020 29th March. This will be the case of Reydesa, which has been included in essential activities regarding annex 18 of the RD-ley10/2020 29th March. At this stage, the staff in trying to contact by email with the previous selected suppliers to continue with the design of the reactor, however, until the date no answer has been received.

During the summer 2020, new contacts were done and some of the parameters were adjusted, due to the uncertainty of some needed controllers by the pilot plant. In the offers obtained the design was proposed as flexible as possible to overcome these uncertainties related to the unfinished action B1 in 20 L. Finally, after waiting for the conclusion in action B1, the purchase was launched in the first quarter of 2021. The providers advise the consortium that the building period can take between 3-6 months. Most of the equipment required arrived in June 2021, however, there were some problems and finally all the equipment (10L and 50L) was installed in INATEC by the last quarter of 2021. Along with the design and implementation, optimisation test and adaptation were done from vials to 10L. The problems with the equipment were the following:
- The 10L reactor had a design defect for the evacuation of the PCBs since in its first cleaning the material got clogged and cracked, rendering it unusable.
- The second 10L reactor came broken from the factory.
- The chiller for the 50L reactor came with expired maintenance and another one was sent from the factory.
- There were some problems with the data acquisition from the pH controller, which were fixed by the factory updating the controller.

Technical deviations:
-Initial technical conditions given by BIOTATEC did not give satisfactory results so optimisation stages were needed in order to guaranteed the technical viability of the process. Moreover, the current conditions can have a further development. It was thought that an optimisation of the concentration of the inoculum.
- The adaption period of microbial consortia was longer than anticipated. Also, there was a delay in the scale up from vials to 1L due to the lack of stirring. In the 10 and 50L reactor the process had a stirrer.
- In the experiment 4, a problem occurred twice, firstly in the 10L reactor and again in the 50L. This test was performed in a higher percentage of solid, and there was a copper cementation of the rod.
It can be concluded that gold is not recovered by applying bioleaching with A. ferroxidans.

All these deviations gave rise to a delay in the finishing date for the action from December 2021 to May 2022.

Deliverable Name	Deadline	Achieved (Yes/No)
B.2.1 Installation report	June 2021	YES
B.2.2 Semi-industrial scale technical report	December 2021	YES
Milestone Name	**Deadline**	**Achieved (Yes/No)**
B.2.1 Pilot Building	June 2021	YES
B.2.2 Mechanical sample preparation on PCB	October 2020	YES
B.2.3 2-step bioleaching process methodology at semi-industrial scale (50L)	December 2021	YES

B3: POST PROCESSING

Foreseen start date: November 2019 Actual start date: March 2021

Foreseen end date: December 2020 Actual (or anticipated) end date: May 2022 (July 2022)

Activities undertaken and outputs achieved

This action comprised 3 tasks:

- B.3.1. Metal extraction from pregnant solutions *(deliverable B.3.1)*
- B.3.2. Cost-effectiveness analysis, project continuation and replication (*deliverables B.3.2/B.3.3)*
- B.3.3. Business plan & study for the patentability *(deliverables B.3.4/B.3.5/B.3.6)*

As a consequence of the delay of action B1, this action B3 was delayed also, finally starting in March 2021.

B.3.1. Metal extraction from pregnant solutions:

A variety of methods to recover selectively metals from leachate generated can be found in literature, it can be either physical methods (adsorption and membrane filtration) or chemical methods (chemical precipitation, solvent extraction, cementation, ion exchange, ion flotation and electrowinning). A review of the suitable methods has been performed, in particular for the methods that can be applied to pregnant solutions, being the most appropriate for the LIFE-BIOTAWEE process leachate: cementation, solvent extraction, ion exchange and selective precipitation reactions.

Given the composition of the pregnant solution, in the selected methods, the extraction of copper will prevail over the rest of the base metals. Finally, the recovery of gold and silver has not been studied due to the low extraction efficiency obtained for both metals in the bioleaching stage, being less than 0.05% for gold and 1-3.6% for silver. The objective was to study the most appropriate methods to recover the copper obtained in bioleaching and at the same time, try to recover the major content of the rest of base metals such as iron and aluminium. Three methods have been applied in order to recover metals from pregnant solutions:

In *precipitation method*, the conditions have been optimized with synthetic sample, in particular removal of iron interference is essential for copper recovery, and also, to determine the most adequate value of pH for selectively precipitation of the other metals that are present in the solution in higher concentration. The results showed a recovery of 99.8% Fe, 45.9% Al, 75.1% Cu, with a purity of 81-92%, 78% and 83% - 88% respectively, and in form of hydroxide or hydrated hydroxide, that should be calcined in case the objective is to obtain metals as an oxide.

The *cementation method* has been also tested to recover copper, and its kinetic constant is affected by the modification of fundamental variables, for this reason, a study of cementation of copper with iron has been carried out, where it has been verified how the following variables affect the efficiency of the process: Temperature, Agitation, Granulometry and pH, and also the use of Zinc instead of Iron. Finally, after the copper cementation, precipitation method has to be applied in order to recover the other metals.

In the *electrowinning method*, the study was focused on the recovery of copper, as it is the majority metal that can be found in the pregnant solution obtained after bioleaching. The variables that can affect the process, and for this reason were studied in detail were the following: Amperage, Interference of other substances, like iron and hydrogen peroxide, pH effect, and copper concentration in the solution. The conclusions showed that the limiting factor was the concentration of copper that has the real sample, which is less than 1 g/L of copper, therefore, this recovery technique cannot be used in this case due to the low viability.

Therefore, after the study of the 3 extraction methods and taking into account the characteristics of the sample obtained in the bioleaching, the cementation technique is selected to extract copper and, subsequently, the precipitation technique to recover aluminium and iron.

Cementation has been selected for copper recovery due to the way in which the copper is obtained. Using the cementation technique, copper is recovered mainly in metallic form and as cuprous oxide, while copper is obtained as cupric oxide by precipitation. In addition, applying the cementation technique consumes less energy. Therefore, copper is recovered by cementation in metallic form and iron and aluminium are recovered by precipitation in the form of iron oxide (III) and aluminium in the form of alumina.

Taking this into account, the final process to be applied to the pregnant solutions consisted on 4 steps: **1) Removal of iron interference at pH4**, **2) copper cementation** with the following conditions: Stirring: 400 rpm, Temp: 50 ºC, pH: 4.0, time: 120 min, and molar ratio Fe/Cu:2, **3) iron recovery at pH 4.2** previously adding hydrogen peroxide to oxidize the iron and **4) recovery of aluminium at pH 7 – 8**. The iron and the aluminium should be calcined to obtain them as an oxide.

Finally, 84-91% of the iron present in the solution, with a purity around 63 – 72 % Fe_2O_3, and 45-53% of aluminium, which purity could not be evaluated due to the insolubility of Al_2O_3, have been recovered. Between 71 and 80% of copper is extracted, it is estimated that a purity greater than 85% can be recovered.

B.3.2. Cost-effectiveness analysis, project continuation and replication
Cost-effectiveness analysis is based on the decision-making carried out throughout the technical development Actions (B1, B2 and B3) that identifies the most economically efficient way to achieve the set objectives in project. Several temporary inflexion points have been chosen in the project execution schedule, where the PMC has made technical decisions that have redirected the evolution of the project and have influenced the achievement of the objectives sought by the proposal. Inflexion points:

After B1 action. Conclusions presented at midterm: In the tests showed in action B1 (250 ml), the leaching of copper comparing the 2-step bioleaching technology (anaerobic+aerobic with Acidithiobacillus Ferroxidans) with 1-step bioleaching (aerobic with Acidithiobacillus Ferroxidans) was shown as to be equal paying attention to copper recovery.
The gas content was shown in action A1 at a lab scale by BIOTATEC setting these values in 47 % CH_4, 20 % CO_2 and 40 % N_2. The conditions of the biogas obtained needs further steps in order to be commercialised and the anaerobic bioleaching takes long times (months) to be treated (which is not cost-effectiveness), so the dismiss of this step seems adequate based on the results given by BIOTATEC. Moreover, the pilot plant was redesigned in a reactor of 50 l because the PMC thought that a better control of the process was priority and reducing the scale up and using 50 l was considered appropriate to provide enough information to define and test a semi-industrial global process in a controllable scale.

After B1 action. How to recover the precious metals contained?
Test carried out to date 31.03.2019 have shown that bacteria considered to carry out the building of LIFE-BIOTAWEE pilot are able to extracting the copper contained in waste but don’t extract the precious metals contained. The consortium proposes to test on laboratory-scale the bioleaching method, with different bacteria, to define the best final extraction method for precious metals. In Deliverable B.1.2. “Bench scale technical report”, updated on

06.05.2022, tests carried out by BIOTATEC to respond to this topic are explained. Results of this trial (Experiment 4 aerobic phase using Chromobacterium violaceum) have served as the basis for the construction of the viability scenarios.

In B3 action. Presented at deliverable B.3.1.
Three methods have been studied for metal extraction in B3 Activity (B.3.1 task). For bioleaching samples, electrowinning method is not technically feasible due to the low concentration of copper (less than 1 g/L in solution). Fractional precipitation and Cu Cementation are technically possible but Fractional precipitation consumes much more energy than cementation treatment. After comparing both methods, the cementation method is chosen as the method for copper extraction. After recovering the copper by cementation, the fractional precipitation technique is applied to extract the aluminium and iron from the bioleaching sample. Therefore, copper is recovered by cementation in metallic form, iron in the form of iron oxide (III) and aluminium in the form of alumina.

Viability study of the process

LIFE-BIOTAWEE process consist of several stages, which are broken down below:
1. Stage 1. Mechanical treatment
2. Stage 2. Cleaning PCB fraction for Bioleaching treatment (not considered in industrial feasibility study)
3. Stage 3. Bioleaching treatment
4. Stage 4. Metal extraction treatment.

CONCLUSIONS:
1. A metal recovery process has been successfully development from waste that is difficult to treat. The process has been defined to extract the valuable metals contained in the NMF of PCBs. It is an environmentally friendly solution compared to other technically feasible options (hydrometallurgy and pyrometallurgy).

- The bio-defined alternative requires a long process time, which could be improved with Microorganism optimization tasks (better adaptation; better control of feeding and pH conditions)
- The bio-defined alternative works in a solid/liquid ratio of 6%. Tests would be needed to Increase the solid/liquid ratio with a view to increasing production capacity and minimizing effluents generated
- The bio-defined alternative works to selectively extract valuable metals such as Cu and Au in two stages:
    Acidithiobacillus ferroxidans bacteria as medium for bioleaching treatment to Cu recovery
    Cyanogenic bacteria as medium for bioleaching and Chromobacterium violaceum culture to Au recovery

2. The LIFE-BIOTAWEE process defined for the 20/80 mix of PCBs (20% Type1 + 80% PCB Type3) is not economically viable. The hydrometallurgical option is considered to assess the economic and environmental feasibility (*see Deliverable C.1.3.)* under the same conditions. The hydro-process continues to be presented as no-viable process.

3. The economic viability of the LIFE-BIOTAWEE process is highly dependent on the metal content of the waste to be treated. The process become economically viable if copper or precious metals content approaches 17% Cu or >50ppm Au.

4. The data used to define the LIFE-BIOTAWEE process on an industrial scale have been extracted from the test carried out:

In the LIFE-BIOTAWEE pilot at a 50L scale (replicated up to three times) where every consumption (energy and reagents) and waste generation have been considered and where the cost of reagents, energy consumption and reagents have been approximated to industrial scenarios.

In the BIOTATEC laboratory at 20L scale (one test) where not every consumption has been considered, neither the waste nor its nature have been quantified.

Results from gold recovery are not considered robust enough. A controlled scaling process is necessary to ensure the data presented in this study.

5. The LIFE-BIOTAWEE service has been defined to recover metal content in difficult-to-treat waste. The waste treatment service is offered whenever there is a content of

>17% Cu or

>50ppm Au

The service as defined can treat up to 304 Tn waste per year and costs 140€ per Tn. The detailed information in *deliverables B.3.2 and B.3.4* can be found.

Replicability:

After the results obtained in LIFE-BIOTAWEE process, the consortium put the focus on another problematic waste stream, suction dust. This residue is the filter dust collected in the suction system of the equipment dedicated to crushing and separating WEEE in the different material streams. This waste is mainly destined to Germany for its recovery in huge refining furnaces in the waste management industry, but it is only accepted when its Cu content is higher than 10%, and depending of the content of other metals like gold, silver or lead. In the case there are not accepted, the only option is landfill or being reintroduced in the process, when the metallic content may be refined. In fact, due to lead content of this waste, the recovery option in Germany has been jeopardized, and searching another type of treatment is required for this waste. In each mechanical treatment, depending on the material being processed, the composition of the filter dust may change so Acidithiobacillus Ferroxidans should be able to adapt to different composition ranges of the waste.

In order to have a wider information about the transferability of LIFE-BIOTAWEE process to treat this waste, two tests were performed using 2 different suction dust. On the one hand, the consortium agreed to give another opportunity to the anaerobic bioleaching using suction dust due to its properties (more appropriate grain size and organic material) compared to NMF of PCBs. On the other hand, current conditions of LIFE-BIOTAWEE process were tested in the semi-industrial pilot plant.

<u>2-step methodology (anaerobic + aerobic):</u> This experiment is performed with the sample of zig-zag dust obtained from the mechanical treatment of PCBs, temperature 37°C. The volume of culture medium (R2A) in the reactor was 15L, suspension concentration 1%, inoculum concentration 4%.

- Anaerobic: In this experiment the temperature maintenance was under control, the pH was self-regulated and the gas samples were periodically taken. The only deficiency in this experiment was clogging of gas filter. The maximum content of CH_4 in gas phase was 62%. Interestingly, also the N_2 concentration was rather high (29,4%) at the end of experiment.

- Aerobic: the solid residue from previous anaerobic step was treated in aerobic conditions in the 20 L reactor with 5% pure culture of *Acidithiobacillus ferrooxidans,* 1% suspension, at temperature 30ºC. The viable inoculum for the experiment was obtained from the type culture *Acidithiobacillus ferrooxidans* DSM14882 with two passages, lag phase of the last culture – 7 days.

Conclusions: has showed better results than the ones obtained for NMF of PCB, indicating that its application could be successful for other type of waste.

<u>1-step methodology (aerobic):</u> At 50L scale in aerobic conditions, 30ºC with controlled pH 2 with *Acidithiobacillus ferrooxidans* for 12 days a sample of filter zig-zag was treated.

Conclusions: The extraction yield obtained for Cu reach the 98%, and 69% for Al. Other metals are also recovered, taking into account that its content in the initial waste is lower than 1%, that is the case of Zn 64%, Ni 51% or Sn 7%. In the case of Au bioleaching, the content in the liquid after bioleaching is under the limit of detection, and it can be concluded that this method is not adequate for Au recovery.

<u>1-step methodology (aerobic):</u> Aerobic bioleaching tests with Acidithiobacillus ferroxidans with different types of suction dust generated in the mechanical treatment have been realized in laboratory scale. Its adaptation till 10 g/L of dust were performed successfully, at 30ºC with controlled pH 2.

As it was mention before, suction dust is a waste commonly obtained in the mechanical treatments apart from PCBs treatment. Therefore, is a generalised waste obtained in several industries that may be treated using LIFE-BIOTAWEE process. It can be concluded that the applicability to these residues could be properly performed

Another replicability possibilities:
Phosphogypsum (PG) residue:
The knowhow gained during BiotaWEE project has helped us to develop novel methods for converting these industrial waste streams to sources of critical raw materials. BiotaTec's technology for extraction of REE-s from PG is capable of removing 70-90% of Ce, La, Nd, Pd, Sm, Eu, Gd in as short time as 6 hours.

Municipal Solid Waste (MSW):
MSW Management industry generates fly and bottom ash. There are eleven incineration plants in Spain capable of treating 10% of the annual volume of MSW generated on a national scale. Otua Group treats the bottom ash generated in one of the MSWM industry in the Basque Country (Spain). The finest fraction, approximately 20-40% by weight of flow, is released from the input material to facilitate subsequent metal recovery treatment. But finest fraction separated, with metallic content and high economic value, goes to non-hazardous waste landfill.

Bauxite Residue (BR):
BR is a leftover of Bayer process of alumina extraction from bauxite ore. It contains high amounts of iron (hence its color by which it is colloquially known as red mud) along with many other metals, several of which are classified as critical raw materials. These include REE-s, especially scandium and other metals such as vanadium. The content of these metals is in the range of tens to hundreds ppm-s, but given the annual global BR production is more than 100 million tons, the amount of neodymium alone (a necessity for every electric car and wind turbine) is roughly on par with current global production.

Lithium-ion batteries (LIBs):
The focus on the treatment of black-mass generated from mechanical treatment of the LIBs extracted during WEEE decontamination processes was put. Using aerobic bioleaching with Acidithiobacillus ferroxidans, Co, Ni and Li can be extracted. Reydesa has opted to a new project where the main objective is to investigate, apply and validate a sustainable and innovative bioprocess to recover embedded Li with advanced and intelligent digitalization that, given its high value in the market, allows adding value to the entire chain in the bioleaching process for the recovery of lithium from the metal concentrate (black mass) obtained from the mechanical treatment of LIBs from the LFP type (with $LiFePO_4$ cathode), which is the future in the short/medium term in the battery manufacturing sector.

Continuation:
BiotaTec is developing further strategies for valorisation of e-waste with grant from Estonian Government and EU as well as raising additional capital.
The aim is to further develop and improve the bioextraction technology of various metals from different types of e-waste.

Additionally, it will be explored the possible ways to increase the overall value of e-waste leaching process through biosynthesis of metallic nanoparticles.

Commercialization agreement:
The commercialization agreement has been prepared and it being discussed by the legal

advisory departments of REYDESA and BIOTATEC. *Deliverable B.3.6*

B.3.3. Business plan & study for the patentability
After the conclusions extracted from the cost-effectiveness analysis, Reydesa saw the viability of implementing a service for the treatment of several WEEE wastes if the composition constrains are achieved. The business plan for this service is described in deliverable B.3.4.

Business plan:
LIFE BIOTAWEE business area will offer the management service for difficult-to treat waste from electrical and electronic equipment waste processing in recycling plants by mechanical treatment. This service will meet two critical needs:
1. Provide recycling industries with a feasible and environmentally friendly alternative to not disposing of waste in landfills, and
2. It will help meet the demand for metals (copper and precious metals).

Our recycled materials will be destined for industries that produce copper and precious metals. Potential customers will benefit from recycled metal concentrates with a purity not common in this market.

The service has been defined based on the treatment of the NMF of PCBs, material with a high content of copper and precious metals, defined as waste and usually destined for landfills. Within the framework of the project, other waste generated in the mechanical treatment of WEEE has been managed with LIFE BIOTAWEE technology and its applicability has been tested.

The LIFE BIOTAWEE service will offer a new concept of waste management that is difficult to treat in the metal recycling plants. Currently, these plants face several problems related to the disposal of filter dust (suction dust) (with high copper content and sometimes precious metals content) that is not always well received by the waste management and metal refining industry. If this industry does not accept this material, it should be sent to specialized landfills.

Landfills are filling up and disposal costs are rising. LIFE BIOTAWEE service is entering a market niche where filter dust has not been recycled on any significant scale in Spain or Europe. This is a unique and viable concept that addresses the needs of various clients and reaches an untapped market with tremendous growth potential.

One of the most attractive aspects is that the business is projected to achieve a strong cash position and achieve profitability in the third year of operation. Due to the great need for these products and services and the lack of direct competition, our projection of rapid profitability is feasible not only due to the sale of the service under payment of waste management, but also the sale of the service under payment of transfer of knowledge.

In-depth research related to the composition of the waste that could be treated by the service is well advanced. The concept has been tested on a small scale and the results, after analysis, turned out to be high purity metal concentrates. The investigation will be an ongoing process for the company.

SERVICE DESCRIPTION
Reydesa will receive the material at its industrial facilities, from its mechanical treatment lines and/or from external companies interested in the LIFE BIOTAWEE service.

The material proposed for LIFE BIOTAWEE service will be limited based on its metal content:
• Cu (>17 wt. %) and/or
• Au (>50 ppm)
Only the material that exceeds the limits in terms of content will be treated.
The material generated or received will be analysed base on:
• Target metal content: Cu, Au, Ag with a view to defining the treatment/valorisation process.
Subsequently, it will be destined for a screening pre-processing at <2mm.
The recycling process will last 5 days. At the end of the five days, the residue will be converted into recoverable metal concentrates in the metal market at current market cost, considering its purity.

Patentability:
Based on the anaerobic experiments with PCBs of WEEE in 20 L reactor, amendments were made to the patent pending EP3416759 „Method for decomposition of the metallorganic matter of graptolite-argillite by microbial consortium “.

BIOTATEC has conducted a preliminary FTO study revealing that currently there are no related patents from other parties that would conflict, or which would be infringed in the development and application of the technology. A professional patent attorney would be subcontracted for more thorough analysis.

<u>Deviations and main problems:</u>
As it was mentioned before in the Mid-term report, in the grant agreement, the activities related to the bioleaching process (B2.3 Set-up and operation) and post-processing (B3.1 metal extraction from pregnant solutions) and the lab task inside B3.2. related with the transferability of the process using another waste stream, were done in the facilities of INATEC instead of in REYDESA's plant. This change obeyed to the difficulty founded by the consortium in the technical working operations of the bioleaching process and the conditions needed for the reactions. The process was better controlled in the laboratory area than in the designated area in the plant. Also, it has to be taken into account, that experts decided to change the material of bioreactor from steel to glass and decrease the volume to 50 l to have a better control of the reactions performed. The consortium selected to address these stages in the chemical lab in INATEC, performed by the laboratory technicians and the supervision of the researchers and the innovation manager. To sum up, to tackle these technical challenges a conversion of the number of hours set for REYDESA in action B3 were performed by INATEC as it was thought a better way to cope the objectives presented.

Technical deviations:
In order to fulfil the global scope of BIOTAWEE project a recovery of precious metals should have been done (mainly Au and Ag). The initial proposal was the treatment with the 2-step bioleaching, being the aerobic phase performed by Acidithiobacillus ferroxidans. As it was show in the experiments of action B1, these microorganisms cannot extract precious metals so other bacteria was proposed to accomplish this aim. The problem founded is related to the risk level and the restrictions of use of these bacteria. Chromobacterium violaceum is categorised as risk group: 2 (classification according to German TRBA) and restrictions: Category A1, Act dealing with the prevention & control of infectious diseases in man. The use of these bacteria requires a global transformation of INATEC's laboratory as the culture is marked with the bio-hazard label and currently INATEC's laboratory is unable to perform experiments with the security required by the bacteria.

Milestone Name	Deadline	Achieved (Yes/No)
B.3.1 Post-processing methodology	December 2021	YES
B.3.2 Cost-effectiveness assessment	May 2022	YES
Deliverable Name	Deadline	Achieved (Yes/No)
B.3.1 Post-processing technical report	December 2021	YES
B.3.2 Cost-effectiveness analysis	July 2022	YES
B.3.3 Replicability and transferability plan	July 2022	YES
B.3.4 Business plan	July 2022	YES
B.3.5 Report on the patentability of the BIOTAWEE solution	July 2022	DELAYED October 2022
B.3.6 Licensing agreements	July 2022	YES

C1: MONITORING OF THE ENVIRONMENTAL IMPACT OF THE PROJECT

Foreseen start date: Junio 2019 Actual start date: Junio 2019

Foreseen end date: December 2020 Actual (or anticipated) end date: June 2022 (July 2022)

Activities undertaken and outputs achieved

This action comprised 3 tasks:

- C.1.1. Monitoring of the environmental impact and updating of performance indicators table
- C.1.2. Update of the LIFE KPI Webtool
- C.1.3. Life-cycle assessment

C.1.1. Monitoring of the environmental impact and updating of performance indicators

The main environmental aspects to measure and evaluate its improvement are the following where it is compared the proposed situation in 2017 with the actual situation after the project execution:

Reduction of dangerous substances/waste management:

Reduction of the total amount of material to be treated with dangerous substances to recover the very valuable metals from the residue. The aim was a reduction in hazardous waste generation of 0.3 Tn at the end of the project respect a complete hydrometallurgical process.

Table 1. Waste generated comparative, Biometallurgy vs Hidrometallurgy.

Treatment	Waste generated to treatment (T/T treatment)		Waste generated to reuse (T/T treatment)	
	Solid	**Aqueous**	**Solid**	**Aqueous**
Biometallurgy (Cu, Al, Fe, Au)	0.00	1.12	0.28	3.51
	1.12		3.79	
Biometallurgy (Cu, Al, Fe)	0.33	0.62	0.00	1.94
	0.96		1.94	
Hydrometallurgy (Cu, Al, Fe, Au)	0.80	5.00	0.00	0.00
	5.80		0.00	

Biometallurgy (Cu. Al. Fe): 1-step aerobic bioleaching. Data extrapolated from BIOTAWEE process performed by REYDESA at semi-industrial scale.

Biometallurgy (Cu. Al. Fe. Au): 2-step aerobic bioleaching. Data calculated from BIOTAWEE process performed by REYDESA at semi-industrial scale for the first aerobic step (a. ferroxidans) and extrapolated from BIOTAWEE process performed by BIOTATEC at lab scale for the second aerobic step (Ch. Violaceum).

Hydrometallurgical data is extrapolated using the data obtained in research project performed by Reydesa-Inatec at lab scale. The data of waste generation is very conservative.

The critical difference between biometallurgy and hydrometallurgy is the need in hydrometallurgy of using great quantities of organic solvents that has to be treated after the use. Moreover, the typical extraction stage used in hydrometallurgy as acid digestion, is non selective. Base metals and precious metals are leached together, so after extraction there are several metals to be recovered and the complexity of the matrix and the solvents and stripping phases are multiple.

5 Tn of organic/aqueous solvents to be treated by 1Tn PCB vs 1.12 Tn /Tn PCB to be treated in 2 step aerobic bioleaching process, so 3.88 Tn waste management is reduced. The objective is accomplished, more than the 70% of hazardous waste is reduced (77.6 % of the effluents to be treated). According to solid waste, hydrometallurgy has 0.80 Tn vs 0 Tn to be treated. This is because the solid waste contained Au is fed into the second aerobic bioleaching and after this second bioleaching the solid waste does not contain hazardous metals so there is no need for treatment and can go to landfill or current possibility is to constructive industry.

5 Tn of organic/aqueous solvents to be treated by 1Tn PCB vs 0.62 Tn /Tn PCB to be treated in 1 step aerobic bioleaching process, so 4.38 Tn waste management is reduced. The objective is accomplished, more than the 70% of hazardous waste is reduced (87.6 % of the effluents to be treated). According to solid waste, hydrometallurgy has 0.80 Tn vs 0.33 Tn of 1-step, thus 58.75% of reduction.

The management of hazardous expected wastes could be between 65 € - 120 € / Tn.

To sum up. Both BIOTAWEE processes reach the proposed reduction in hazardous waste generation respect a complete hydrometallurgical process.

Detailed explanation in deliverable *B.3.2 Cost-effectiveness analysis.*

Reduction in resource consumption:
It was stated a reduction of 50% in raw material.

MATERIAL	Recovery (Kg/T PCB)
FERRIC	102,80
Al	28,86
Fe	263,71
Cu	25,13
TUBE LOSSES	18,10
FILTER DUST HIGH DENSITY	13,40
FILTER DUST LOW DENSITY	155,40
HEAVIES	67,50
1ST CLASS A	159,80
1ST CLASS B	38,90
2ND CLASS	45,10
Au	0,01
TOTAL	**918,72**

Al, Fe, Cu and Au are the raw materials recovered from the 2-step aerobic bioleaching processes. If it is considered only 1-step 0,01 kg of Au should not be counted in the recovery.

These quantities are directly recovered from the NMF of PCB per Tn of PCB and should be added to the rest of the material recovered. Except for the Au and Ag extraction, the rest of base metals have an extraction superior to 50%, so the recovery is achieved for base metals. In the case of Ag, the extraction is around 1% so no recovery should be counted and for the Au, the preliminary test shows a recovery of 45% that must be optimised in order to increase the quantity.

Energy:
100% reduced energy consumption. This reduction was based in the impact of the generation of CH_4 in the global consumption of the process. Since the generation of CH_4 in the anaerobic phase for the treatment of NMF of PCBs was not satisfactory, this reduction was not possible.

Treatment	**Energy Cost (kwh/Ttreatment)**
Biometallurgy (Cu, Al, Fe, Au)	2.477
Biometallurgy (Cu, Al, Fe)	1.238
Hydrometallurgy (Cu, Al, Fe, Au)	331

Biometallurgy (Cu, Al, Fe): 1-step aerobic bioleaching, data calculated from BIOTAWEE process at semi-industrial scale.
Biometallurgy (Cu, Al, Fe, Au): 2-step aerobic bioleaching, data calculated from BIOTAWEE process at semi-industrial scale for the first aerobic step and calculated/estimated from BIOTAWEE process from the lab scale test for the second aerobic step.
Hydrometallurgical data is calculated using a research project performed by Reydesa-Inatec at lab scale for 1Tn of PCB.

The main advantage in hydrometallurgy vs biometallurgy is the residence time of each experiment. In hydrometallurgy, the leaching in several hours may be done, however in biometallurgy the residence time is conditioned to the adaptation of the bacteria to the waste. If there are a population well adapted, the leaching may be done in 5 days in optimised conditions.

This environmental aspect is not achieved.

CO_2:
Taken into account as reference: Electricity 0.258 Kg CO2/kWh (Oficina Española de Cambio Climático, 2021).

Treatment	**Energy Cost (kwh/Ttreatment)**	**Tn CO_2/ Tn treatment**
Biometallurgy (Cu, Al, Fe, Au)	2.477	0,64
Biometallurgy (Cu, Al, Fe)	1.238	0,32

Hydrometallurgy (Cu, Al, Fe, Au)	331	0,09

As this environmental aspect is related to the electricity consumption, the reduction is not achieved also.
Detailed explanation of each environmental aspect in deliverable *B.3.2 Cost-effectiveness analysis.*

C.1.2. Update of the LIFE KPI Webtool

The update of the LIFE KPI WEBtool it has been made in October 2022. More detailed description in *deliverable C.1.2. or in the WEB*

C.1.3. Life-cycle assessment:

Introduction: The functional unit (FU) is the Treatment of one ton of printed circuit boards, to obtain precious and base metals. System range is defined as “cradle to door” range, at this level of scope, those stages subsequent to the end of the treatment stage (transport to client, use and end of life) are excluded. The limits of the system are the following ones:

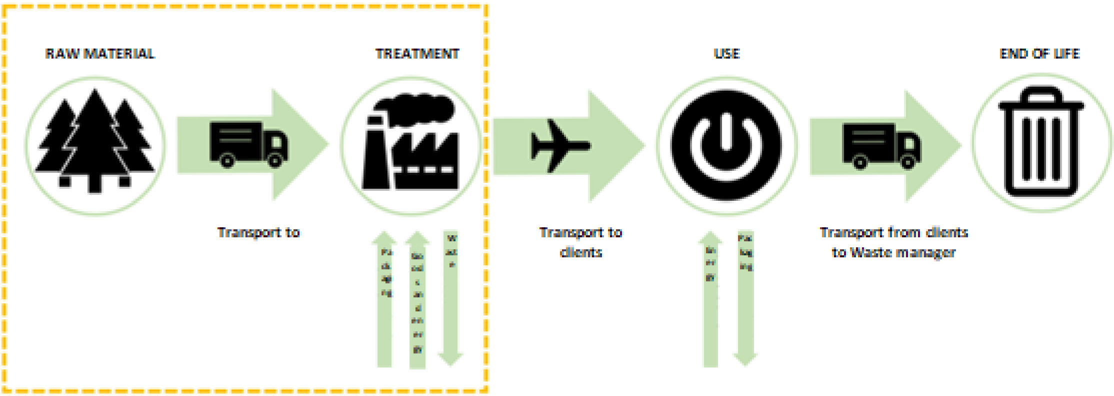


Figure 8. Limits of the system.

This LCA has been developed according to ISO 1040/1044 Standards and in line with the ILCD guidelines. The Ecoinvent 3.8 database together with version 1.8 of the OpenLCA software have been used to create the LCA, due to its extensive information and number of environmental indicators.

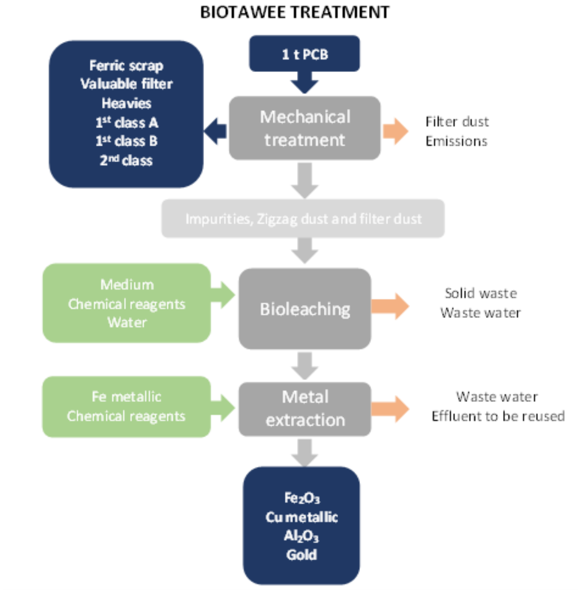


Figure 9. LIFE-Biotawee process.

Two bioleaching steps have been taken into account, both aerobic: A. ferroxidans for extraction of base metals followed by C. violaceum for the extraction of precious metals. The transport of the PCB for the BIOTAWEE technology has been omitted, since the distance from the supplier to the facilities of Reydesa Recycling (of the Otua Group), where this waste is treated, is less than 1 km. In those cases where the distance between the plant and the waste management plant is unknown, an average distance of 50 km has been defined for the waste generated during the manufacturing/treatment stage. No cut-off criteria or product allocation criteria have been applied.

The electrical consumption of the mechanical treatment has been estimated based on REYDESA's usual consumption per annual treated ton, estimating 70% of this value. In the processing of printed circuit boards, not all facilities are used, but the shredder with higher consumption is used. These estimates include consumption by the air aspiration and purification system, from which the suction dust is extracted. The impact assessment used in this evaluation is the ei – EF V3.0, and not weighting or normalization has been used.

Data: In the global computation, the environmental reduction offered by the LIFE BIOTAWEE technique is evident, followed by the hydrometallurgical treatment, being the worst option pyrometallurgy. Taking this into account, and counting pyrometallurgy as maximum value among the options, its direct comparison of the total cycle impact of the study treatments can be observed in Table 2.

Table 2. Direct comparison of the total life cycle impact of the study treatments, with the pyrometallurgical treatment as a reference, with the single score.

Impact category	Unit	Pyrometallurgy	Hydrometallurgy	BIO-TAWEE
Single score (total)	%	100	- 33.1%	- 76.9%

Hydrometallurgy has a 33.1% less impact than pyrometallurgy, reduced even more by BIOTAWEE, with a single score that is 76.9% less than pyrometallurgy. In Figure 10**¡Error! No se encuentra el origen de la referencia.** Can be observed the results obtained per category impact, with values scaled out to the maximum value per impact category. Also, the difference between LIFE BIOTAWEE option and the other techniques are also analysed

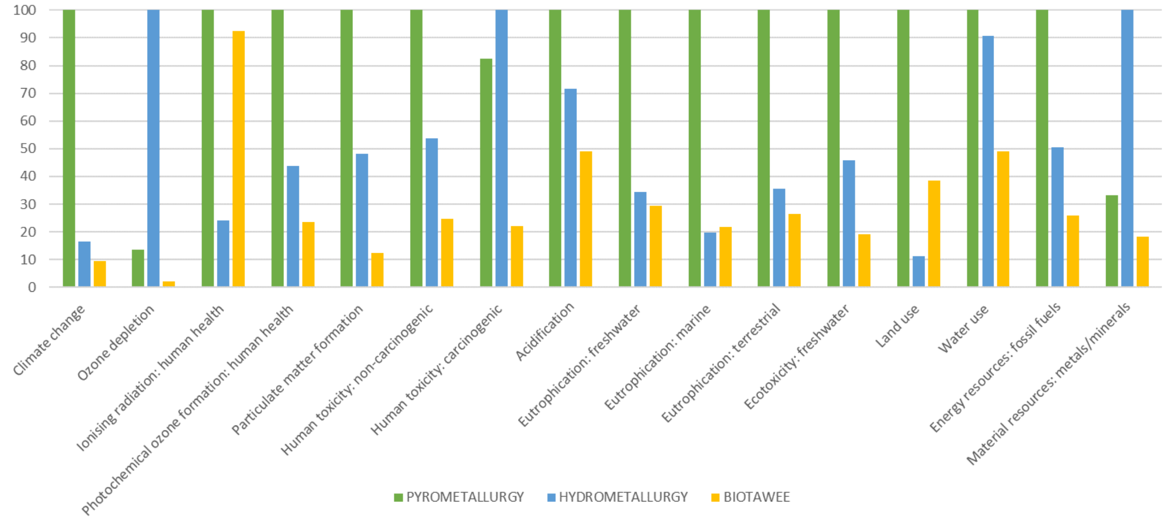


Figure 10. Results in a single score of the total impact characterized by impact category for the teams defined in the study, with values scaled over 100 to the maximum value per impact category.

BIOTAWEE option has always lower impact than pyrometallurgy, but in comparison with hydrometallurgy, ionising radiation, eutrophication marine and land use are worst in the BIOTAWEE use case, taking into account the estimations done in this study.

Analysis by step in LIFE BIOTAWEE process. Additionally to the LCA comparison with other treatment options, the analysis by step is also performed, and the results in single score can be observed in Figure 11.

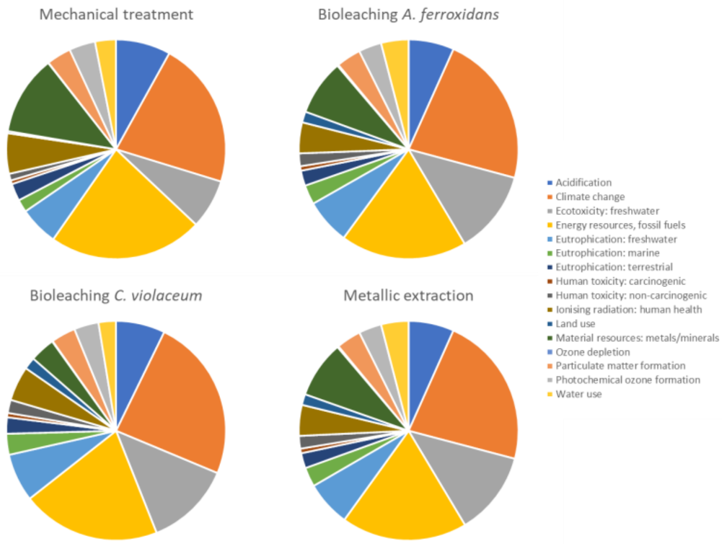


Figure 11. Impacts per step in the BIOTAWEE process.

In this case, the functional unit is not the same and for this reason it is not possible to compare the steps among them. In the mechanical treatment, 1 ton of PCBs are processed in order to obtain the impurities and other fractions that will be further processed in the bioleaching steps. From this ton, only 400 kg are processed in the first bioleaching step, and after this treatment, the quantity to be processed in the second step of bioleaching is even lower. In the metallic extraction, the treatment is focused on the metallic extraction of the pregnant solution from the both bioleaching processes.

It can be observed that in all the cases, the main impacts are Climate change and Energy resources – fossil fuels; being the lower impacts human toxicity carcinogenic and no carcinogenic, land use and ozone depletion.

In the mechanical treatment, as it is highly intensive in electric energy, the main impact is energy resources – fossil fuels with a 22.7% of the total impact, followed by climate change with a 21.7%, and material resources-metals/minerals with an 11.7%.

For the other steps, bioleaching with A. ferroxidans, bioleaching with C. violaceum, and metallic extraction, the main contribution is climate change (22.5%, 24.06% and 22.41% respectively), energy resources – fossil fuels (18.6%, 20.4% and 18.5% respectively) and Ecotoxicity freshwater (12.3%, 12.7%, and 12.3%). This is because the three steps are based on the high consumption of chemical reagents, in a complex mixture as it is the case of the medium 882 in the first step of bioleaching, or the high consumption of sodium hydroxide in the metallic extraction; and both bioleaching counts with a high energy consumption, even greater than the mechanical treatment, due to requiring of heat and agitation during long periods of time.

CONCLUSIONS:

In order to contribute to achieving a model of sustainable development in society, methodologies and tools capable of quantifying and evaluating the environmental, economic and social behaviour of goods and services are required. This goal is closely linked to the Sustainable Development Goals (SDGs) established by the United Nations.

In this sense, one of the available tools is the Life Cycle Analysis, which allows identifying and evaluating the main environmental, economic and social impacts associated with each of the stages of the life cycle of a product, process or activity.

LIFE BIOTAWEE technique for metals extraction has notably demonstrated a life cycle environmental improvement (cradle-to-gate) of 76.9 % in aggregate impact potential values (Pt), compared to pyrometallurgical treatment (which is the method commonly used), and 43.84% compared to hydrometallurgy.

The impact categories that have the most significance in the impact of the treatments are climate change, ecotoxicity in freshwater, Energy resources – fossil fuels and material resources- metals/minerals. For pyrometallurgy, the most important impact is climate change, with a contribution of 39.45%, in hydrometallurgy and LIFE BIOTAWEE process, material resources-metals/minerals is the category with a higher contribution to the global impact, obtaining a 54.28% and 28.46% respectively.

This is due to the high quantity of reagents required for the hydrometallurgical and BIOTAWEE treatments, compared with pyrometallurgy, that requires of more energy.

One of the most important aspects to highlight in the comparison of processes is the logistics aspect. Considering that the pyrometallurgical process is carried out in Germany, the impact associated with the transport of the PCBs to the plant is considerable.

In this aspect, carrying out a sensitivity analysis of the distance travelled by the printed circuit boards from the collection point to the processing/treatment plant, it is concluded that: the pyrometallurgical treatment of PCBs shows a more favourable environmental behaviour than the technique of hydrometallurgy, as long as the distance from the origin to the plant is less than 200 km.

But it could be also be concluded that even reducing the distance to zero, the Pyrometallurgical process will never show less impact than the LIFE BIOTAWEE process. In short, the environmental performance of the processes is closely related to two important aspects: on the one hand, the different product outputs for techniques; on the other hand, the relevance of the distance to the management company. These two variables influence the results, being decisive in the environmental comparison of both processes. Therefore, both aspects will be key in identifying the most recommended process.

LIFE BIOTAWEE process has been also analysed in detail, in order to evaluate the main impacts of each step, and, in all the cases, the main impacts are Climate change and Energy resources – fossil fuels; being the lower impacts human toxicity carcinogenic and no carcinogenic, land use and ozone depletion.

In the mechanical treatment, the main impact is energy resources – fossil fuels due to the electric energy consumption of this step is the main contribution to its impacts, apart from the dust generation.

In the case of the bioleaching steps the energy consumption is greater than the one estimated in the mechanical treatment, due to requiring of heat and agitation during long periods of time. This situation, in conjunction with the high consumption of chemical reagents for the preparation of the medium, produces that the main impacts of these steps are climate change, energy resources – fossil fuels and Ecotoxicity freshwater.

In the step of metallic extraction, the consumption of high quantities of sodium hydroxide, and the requirement of heat, produces that the main impacts of these steps are climate change, energy resources – fossil fuels and Ecotoxicity freshwater. In order to reduce the overall impact of LIFE BIOTAWEE process, electric energy consumption of bioleaching processes should be reduced, effluents should be reused to a more extent and the use of reagents in the metallic extraction should be reduced.

Even taking into account that, it should be outlined that LIFE BIOTAWEE option has always lower impact than pyrometallurgy, and also with hydrometallurgy, defined as mechanical treatment followed by chemical leaching. Only in the impacts of ionising radiation, eutrophication marine and land use, are worst in the BIOTAWEE use case compared with hydrometallurgy, taking into account the estimations performed in this study.

Deviations and main problems:

At the time of the end of the project two indicators were removed from the KPI webtool. The indicators were:
4.1.1. Resource efficiency – energy consumption
4.4. Resource efficiency – circular economy

These two indicators were related to the generation of methane in the anaerobic process. The methane produced, would have been used reducing the electric consumption and increasing the circular economy. Since, the generation of methane has not been properly demonstrated with the NMF of PCBs, the achievement of these indicators is not feasible.

Milestone Name	Deadline	Achieved (Yes/No)
C.1.1 Monitoring report: Initial situation	October 2019	YES
C.1.2 LIFE KPI Weebtool update and related explanation in Midterm report	February 2020	YES
C.1.3 Monitoring report: Final situation after implementation of the project	July 2022	YES
C.1.4 LIFE KPI Weebtool update and related explanation in Final report	October 2022	YES
Deliverable Name	Deadline	Achieved (Yes/No)
C.1.1 Updated LIFE Project Specific Indicators at the time of the Midterm Report Initial indicator report.	October 2019	YES
C.1.2 Updated LIFE Project Specific Indicators at the time of the Midterm Report Initial indicator report.	October 2022	YES
C.1.3 LCA related to BIOTAWEE technology	July 2022	YES

C2: MONITORING OF THE SOCIO-ECONOMIC IMPACT OF THE PROJECT
Foreseen start date: January 2020 Actual start date: January 2020
Foreseen end date: December 2020 Actual (or anticipated) end date: June 2022 (July 2022)

Activities undertaken and outputs achieved
This action comprised 2 tasks:
- C.2.1. Analysis of the technology implementation
- C.2.2. Estimation of socio-economic impact

C.2.1. Analysis of the technology implementation
There are no known companies dedicated to the treatment of PCBs at the national level, although it is known that the company Atlantic Copper, the largest producer of copper and sulfuric acid in Spain, is contemplating the construction of a treatment plan for 60,000 tons of metallic fractions containing copper, gold, silver, palladium, platinum, tin and nickel, which are contained in old electrical and electronic equipment (WEEE).

For a company dedicated to metal production or metal recycling, it is easier to manage a new waste treatment line with metal content, it is the case with the LIFE-BIOTAWEE process, due to the knowledge accumulated in the field of production or recycling, the client portfolio for the purchase/sale of the raw material or by-products generated and the already existing administration, logistics, analysis and management departments, necessary for the complete definition of a new process. For this reason, it is considered a new line of treatment within an existing company (LARGE or SME company).

The recovery service for the non-metallic fraction of PCBs requires an investment of €1,116k; 3-4 people to carry out metal recovery tasks in the treatment line; the waste material to be treated must contain >17% Cu or >50ppm Au; the productive capacity of the process must be 58-304 tons per year (corresponds to the non-metallic fraction of 6% of all the PCBs collected in Spain during a year); the price of the service must be >140€ per Ton; the added value of the company will be €1M in the third year of activity and the return on invested capital will be in 2026.

C.2.2. Estimation of socio-economic impact
The update of the LIFE KPI WEBtool it has been made in October 2022. More detailed description in *deliverable C.1.2. or in the WEB*

Deviations and main problems:
No deviations detected.

Milestone Name	Deadline	Achieved (Yes/No)
C.2.1 Edition of socio-economic impact monitoring report	July 2022	YES
Deliverable Name	Deadline	Achieved (Yes/No)
C.2.1 Monitoring report: report with the socio-economic initial indicators	December 2020	YES

D: DISSEMINATION AND PUBLIC AWARENESS
Foreseen start date: June 2019 Actual start date: June 2019
Foreseen end date: December 2020 Actual (or anticipated) end date: July 2022

Activities undertaken and outputs achieved
This action comprised 3 tasks:
• D.1.1. Networking with other projects
• D.1.2. Dissemination planning and development of the dissemination pack
• D.1.3. Analysis of synergies with EU policies and policy recommendations

D.1.1. Networking with other projects
Universities and research institutions
Laboratory of Metallurgy at The National Technical University of Athens: meeting with Mr Efthymios Balomenos, a Senior Researcher at the Raw Materials Exploitation & Sustainable Energy Solution. Major topic covered at the meeting was naturally Greek Bauxite Residue – a by-product of alumina production with the Bayer process by which alumina (Al2O3) is produced from bauxite ore. In the given hydrometallurgical process, caustic soda digestion under elevated temperature and pressure is used to leach soluble alumina minerals and subsequently precipitate technically pure aluminium hydroxide. The residual mineral matrix named Red Mud or Bauxite Residue is removed as a by-product from the pregnant leach solution. Based on this collaboration, preliminary tests with Bauxite Residue have been performed in BIOTATEC´s lab in order to found a transferability opportunity for the bioleaching process.

INATEC & REYDESA have collaborated since December 2020 with the University of Basque Country thanks to BIOTAWEE project, in particular with the Chemical and Environmental Engineering Department, 'Biofiltration' Research Group. The work done throughout of the years has made it possible to open new lines of research, preferably within ultimate goal has always been to develop and offer more sustainable technological solutions as an alternative to conventional industrial processes. This collaboration continues nowadays, for the demonstration of the applicability of this biotechnology to wastes with limited treatment. In fact, this collaboration has been established by the preparation of new project proposals to test the application of biotechnology to other waste streams whose application potential has been detected in this project, like lithium recovery from waste produced in the mechanical treatment of batteries.

REYDESA has been also contacted in October 2021 by a student from master's programme at KTH in industrial and environmental biotechnology. In particular, they were searching for companies using bioleaching for the recovery of metals from electrical waste, and they contacted with interest in our project "Life BiotaWEE".

Also, BiotaTec had the honour to give an oral presentation at the Second International Oil Shale Conference (BAU-SIOSC) in Jordan in 2018, has participated in the presentation at the European Research & Innovation Days session "Walking the Talk" organized by the European Institute of Innovation & Technology and European Innovation Council, September 2020 and at biannual Fennoscandian Exploration and Mining Conference, where they could get in contact with several participants interested in the bioleaching technology.

Recyclers and experts in bioleaching

BiotaTec has performed a comprehensive review of companies active on e-waste market in Estonia and mapped their expected interests and positions in the recycling chain. They have contacted all of them and proposed a collaboration to increase their revenue stream by separating base and precious metals from their material (mostly PCB) through bioleaching, and two companies demonstrated readiness to develop such collaboration. The content analysis from crushed PCB-s performed by BiotaTec from one of them (KAT Metal) demonstrated high content of platinum group metals (PGMs). Currently various bioleaching experiments with these materials are ongoing and given the potential for isolation of pure PGMs, they have shown high interest in developing further collaboration.

BiotaTec was visited by CEO of Cronimet, a leading company in Estonia in the field of metal recycling. In this meeting bioleaching technology was introduced in general and also BiotaTec´s specific solutions in particular. Future collaboration by using bioleaching technology to produce pure metals from their raw material was discussed, but decision is currently pending.

BiotaTec was approached by company Fortech based in Costa Rica with the proposal to use our e-waste bioleaching technology in a new plant that will be built in Costa Rica. This company reached out after finding the information on BiotaTec through public data associated with BiotaWEE project. Negotiations are currently ongoing.

Networking with other projects
REYDESA and INATEC did some contacts in order to evaluate synergies:
LIFE DRONE (LIFE19 ENV/IT/000520)
REYDESA was contacted by Eco Recycling S.r.l., a R&D Italian company specialized in the development and implementation of innovative processes and plants. It aims at technology transfer in the field of innovative processes for the treatment and recycling of e-wastes.
Eco Recycling is currently an associated beneficiary of the LIFE DRONE (LIFE19 ENV/IT/000520) "Direct pROduction of New Electrode materials from battery recycling" (https://www.lifedrone.eu/). Life DRONE (LIFE19 ENV/IT/000520) is a project co-financed under the LIFE+ program and aims to demonstrate the environmental and economic feasibility of an innovative process for the recycling of different types of spent lithium-ion batteries, the recovery of graphite and the direct synthesis of cathode material for the construction of new NMC batteries without the need to separate metals individually.

LIFE SEDREMED (LIFE20 ENV/IT/000572)
LIFE SEDREMED is an EU-funded project for the development of an innovative solution to decontaminate polluted marine sites. The project intends to demonstrate the efficiency of a methodology based on bioremediation and electro-kinetics for the decontamination of coastal marine sediments. The project partners will develop a prototype for the application of microorganisms within the sediments and increase their bioremediation capacities thanks to the transmission of electric current, initially at laboratory-scale and then scaled-up on-site.

The intervention will aim expecting the concentration of organic contaminants (such as PAHs, PCBs, PCDDs) and the bioavailability of heavy metals like Pb, Hg, Cd, Cu, Zn and As. The project will showcase a new approach to avoid environmental risks and reduce financial costs incurred in dredging activities and ex-situ treatment of contaminated sediments.

This project has been contacted by REYDESA, but the date for a networking meeting is still pending.

REYDESA participates in CircThread, a project that receives funding from the European Union's H2020 programme under Grant Agreement No. 958448, entitled Building the Digital Thread for Circular Economy Product, Resource & Service Management. The objective is to interconnect the information along the life of a product, from concept to retirement, so that it can be easily accessed and shared.

To make this information available, it is going to be developed, tested, and shared an open-source software platform within the next four years. It will enable digital exchanges of data across the extended product life cycle. Biotawee project has been introduced to the consortium, as a new technique for recovery of metals, because one of the main aims of the project is the recovery of critical raw materials from the WEEE.

D.1.2. Dissemination planning and development of the dissemination pack
From previous report, a communication plan has been developed (D.1.1. Communication Plan). Mentioned plan was created with the aim of guarantee from the beginning the provision of strategic planning and effective management of communication and dissemination activities and tools. On December 2018, the project web was published (www.biotawee.com) All the details in LIFE_BIOTAWEE_D.1.2. Project website. To ensure reaching the widest possible audience, the web has been made in 3 languages: English, Spanish and Estonian.

In this period a project logo was developed. In addition, 3 roll-ups were designed and printed (One for BIOTATEC, other one for REYDESA and the last one in INATEC). As well two posters and a Leaflets (500 units)

New dissemination from Mid-term report:
Workshop/Webinar
BIOTATEC:
- Menert, A. (2021) Project BiotaWee and urban mining in the lab / Projekt BiotaWee ja linnakaevandamine laboris. On December 10th, 2021, BiotaTec OÜ organized an online/ local seminar in Tartu on electronic waste management. Anne Menert, from BIOTATEC / University of Tartu presented the project activities performed by BIOTATEC, action A1 and B1, including an introduction of the project and the explanation of the main conclusions that were extracted from the work performed.

REYDESA/INATEC:
- Montes, N. and Dosal, E. (2022). The recycling industry is committed to biotechnology to recover waste of difficult treatment / La industria recicladora apuesta por la biotecnología para valorizar residuos de difícil expected. REYDESA organized together with Aclima, Basque Environment Cluster, an online webinar on July 14th, 2022 for the presentation of the results of the LIFE-BIOTAWEE project, entitled "The recycling industry is committed to biotechnology to recover waste of difficult treatment". In this project, the attendees were able to ask questions and some of them showed interest in the project

Conferences:
BiotaTec had participated in:
- Annually in the Raw Materials Weeks since 2018 organised by the European Commission. It was a unique opportunity for the raw materials community to discuss

and exchange on all relevant issues: policy, technology, international cooperation, framework conditions, knowledge base etc.

- Biomining '21, 7-10 June 2021, which was the postponed Biomining '20, affected by the Coronavirus outbreak.
- The Pitch presentation at the Raw Materials Forum 23-24 May 2022, Berlin.
- PwC to participate in Wolves Summit in Vienna, October 2022, as a champion of "Net Zero Future – Climate Tech Top50 of CEE"
- In addition, BiotaTec's CEO will be introducing their accomplishments and establishing new contacts with interested parties in Batteries Event 2022 in Lyon from 18th to 22nd October and in EU Raw Materials Week (14th to 18th November).
- procurement calls organized by EIC Business Acceleration Services team, and successful selection by various industries like Azoty, Solvay, Saint-Gobain, etc

BiotaTec organized:

- on 10th of December 2021 a seminar event with the aim to introduce current situation in e-waste management and recent advantages in bioleaching.

BIOTATEC has been accepted to PROMETIA, an international non-profit association promoting innovation in mineral processing and extractive metallurgy.

Press releases

Otua Group, (2018). Kick-off meeting of LIFE2017 project BiotaWEEE. Otua group website (English and Spanish).

Stepanov, M. (2020) Electronic waste can become the Nokia of Estonia / Elektroonikaromudest võib saada Eesti Nokia. Universitas Tartuensis, 5:21-23 (in Estonian)

The rest of news of the project have been released in the BIOTAWEE project website section.

THESIS

MASTER THESIS: Mäesalu, K. (2021) Investigation of WEEE bioleaching processes / Elektroonikaromude bioleostumise protsesside uurimine. Master Thesis, University of Tartu, 86 pp (in Estonian) http://dspace.ut.ee/handle/10062/7215

BACHELOR THESIS: Khan, J. (2020) Bioleaching of platinum group metals from electronic waste. Bachelor Thesis, University of Tartu, 60 pp.

BACHELOR THESIS: Reppo, P. Description of the microbial community for the bioleaching of WEEE / Elektroonikaromude bioleostamise mikroobikoosluse kirjeldamine. Bachelor Thesis (in preparation).

Publications in technical journals

D. Álvarez Irusta; J. Barrenetxea-Arando; J. Cereceda García; E. Dosal Viñas*; N. García Madariaga; I. Márquez Pérez; A. Masip González, N. Montes Alonso; B. Salas Gómez; A. Ubani Lamarain. La industria recicladora apuesta por la biotecnología para valorizar residuos de difícil expecte/The recycling industry firmly expected45 biotechnology to recover waste with scarce treatment options. (Published in INDUSTRIA QUÍMICA nº103, pag 42, June 2022. ISSN:2340-2113. https://www.industriaquimica.es/kiosco/revista103 - .YwXpDHZBxD9)

Menert, A.; Korb, T.; Orupõld, K.; Teemusk, A.; Sepp, H.; Mander, Ü.; Ilmjärv, T.; Truu, J.; Paiste, P.; Kirsimäe, K.; Menert, T.; Kamenev, I.; Heinaru, E.; Heinaru, A.; Sipp Kulli, S.;

Kivisaar, M. Anaerobic microbial decomposition of recalcitrant organic matter with partial leaching of metals (to be submitted to Letters in Applied Microbiology in June 2022)

Menert, A. Sipp Kulli, S. Kivisaar, M. Microbial degradation of the non-metallic part of printed circuit boards (in preparation)

European patent
Menert, A.; Kivisaar, M.; Sipp Kulli S.; Heinarau, A.; Maidre, T. Method for decomposition of organic matter of graptolite argillite by microbial consortium. Priority number: EP3416759A1; Priority date: 16.02.2016; Status: examination in progress https://register.epo.org/application?tab=doclist&number=EP17712017&lng=en

Layman's Report:
Layman's report available in 3 languages was done by the consortium and it is available to download in digital format from the website and in printed as the final leaflets.

D.1.3. Analysis of synergies with EU policies and policy recommendations

The aim of this study was to provide a better understanding of the synergies of the project with EU policies at European level, and looks at both success stories and lessons learned from encountered challenges, identifying pioneering approaches in stimulating synergies, such as defining the limits that the regulation themselves establish and the search for the best solutions to face them. In a first step, this study will be focused on waste electrical and electronic equipment (WEEE), but, based on the replicability and transferability analysis performed in this project, this technology is applicable to other waste streams, and the potential synergies with other policies will be also analysed. As a final point, an analysis of required legislation for the industrial installation of a LIFE BIOTAWEE solution facility in the Basque Country has been also included.

The main achievements of the LIFE BIOTAWEE project includes the recovery of 60% of metals only in the mechanical treatment of PCBs, obtaining streams with high content in copper, and also 10.2% of ferric scrap, that can be directly sold in order to be used in the production process in refineries or in steelmaking. In those copper refineries, the copper is completely recovered, and also other metals, like precious metals contained in the anode slime, that are sold to refineries specialized in processing this product to recover and refine the precious metals and other elements contained. Additionally, the rejected fraction from the mechanical treatment, with a lower copper content and without value in the actual market, is processed in the project by applying aerobic bioleaching, an 86 – 95% copper, 1-4% silver, 98% Zinc, 76-88.5% Al, 53- 55% nickel and 45 % gold can be recovered. In this way, BIOTAWEE project helps to achieve the recycling objectives set in the Directive 2012/19/EU, and is in line with the circular economy initiatives, at European and local level. Therefore, this project aims to contribute to reducing supply risk and mitigating significant price fluctuations. It is a priority to reduce external dependency on the supply of metals by innovating in recycling processes and optimizing the management of metal scrap. In this project, 182 Kg Cu, 0.24 Kg Ag and 0.021 Kg Au are recovered from 1 ton of PCBs, helping to reduce external dependency of the supply, and increasing the local treatment of this waste generated in the decontamination of WEEE.

Application of the 2-step methodology with anaerobic step generating methane has been applied to other waste, the dust produced in the mechanical treatment of PCBs, tested at bench scale in which the results showed that it could be feasible for the treatment. Results of bioleaching solutions developed in the framework of LIFE BIOTAWEE project can and will be implemented to extract critical raw materials (such as for example light and heavy REE-s) from other types of industrial wastes. With the application of this technology to the recovery of critical raw materials, this project shows a very high synergy with the European Critical Raw materials act, and the communication COM (2020) 474 published as a result of the raw materials crisis derived from COVID-19. As part of the European Green Pact and the new industrial strategy for Europe; it is proposed to reinforce strategic autonomy; in a context where metals are a fundamental part of the ecological transition and the substitution of fossil fuels (decarbonization of the economy). This project supports the Directive 2000/76/EC related to Waste incineration, because avoids incineration of 300 t/year of PCBs, reduction hazardous effluents waste generation of 3.88 Tn/Tn PCB, and 42 % CO2 eq. compared with the hydrometallurgical process.

Main barriers detected are relative to the European List of Waste, that is not specific enough to detect the CRM in the waste streams, or even the presence of PCBs, as there are classified in a generic classification with "components removed from WEEE". But REYDESA is participating in a H2020 project to tackle this problem by increasing the traceability of the CRM since manufacturing, improving not only its recovery, as well the overall environmental performance of the equipment as a product. The recently approved POPs regulation could affect the recyclability of plastics recovered from WEEE, as bromine flame retardants are contained in this fraction, and also could entail more cost in the process of WEEE. All the optimizations and improvements of LIFE BIOTAWEE process that should have to be studied in depth before installing at industrial scale are also analysed, in order to no jeopardize the benefits obtained with the emissions and effluents generated by the process itself.

In the replicability and transferability analysis, the specific legislation that could affect its application to other waste streams is also analysed. Apart from similar wastes produced in the mechanical treatment of WEEE, Black mass is also studied. This material is obtained after the mechanical treatment of Li-ion batteries, that has to be processed by a chemical leaching process in order to recover graphite, other metals, like cobalt, manganese, nickel, among others, and lithium. The European Commission in the draft of the new Battery Regulation, published the first initiative of the actions announced within the Action Plan for the Circular Economy. In this regulation, it proposes a minimum level of recycling efficiency of 65% by weight of batteries and LIBs for January 2025, and 70% for January 2030. In addition, by 2025, all recycling processes must reach rates of recovery of materials of 35% Li, having to reach 70% Li by 2030. The application of LIFE BIOTAWEE technology to these waste streams could produce a reduction in waste diverted to landfill, and increase metal recovery, in particular critical raw materials. Taking into account the results obtained in lab scale, also this project is in line with the Mineral Act that is at the moment being prepared by the EC.

As a last section, an analysis of the legislation that has to be taken into account in order to install an industrial facility of bioleaching is also analysed, based on conversations with the Environmental Government of the Basque Country, in order to complete the overall requirements for the feasibility of this process.

<u>Deviations and main problems:</u>

Networking: There were some problems to find research projects related to bioleaching. This, on the one hand shows the novelty of the process as an alternative for the industry, but on the other hand, in order to form partnerships or enter in the recycling industry, which is a very traditional industry, was problematic. Some of the contacts were unsuccessful, because we did not reach enough interest or there was no feedback.

The technical workshop to disseminate the new technology was done by BIOTATEC in December 2021 instead in Reydesa facilities, however the final conference was held by Aclima with an online presentation guided by Inatec and Reydesa.

Finally, there is task pending which is the printing of the final leaflets that is going to be done out of schedule of the project.

Milestone Name	Deadline	Achieved (Yes/No)
D.1.1 Project web site launching	December 2018	YES
D.1.2 Notice Boards placed in partner's facilities	June 2019	YES
D.1.3 Meeting for Networking with other projects	July 2022	YES
D.1.4 Printing of initial Leaflets	June 2019	YES
D.1.5 Technical workshop to disseminate the new technology in Reydesa Facilities	December 2021	YES
D.1.6 Release of videos	July 2022	YES
D.1.7 Printing of final leaflets	July 2022	DELAYED
D.1.8 Final Conference	July 2022	YES
D.1.9 Layman's report uploaded on the web	July 2022	DELAYED (October 2022)
Deliverable Name	Deadline	Achieved (Yes/No)
D.1.1 Communication plan	December 2018	YES
D.1.2 Project website	December 2018	YES
D.1.3 Notice board, roll up and leaflets	June 2019	YES
D.1.4 Report on Technical publications done	July 2022	YES
D.1.5 Networking report at the end of the project	July 2022	YES
D.1.6 Analysis of synergies with EU policies (EU priorities for growth and the reliable and unhindered access to critical raw materials (CRM))	July 2022	YES
D.1.7 Layman's report at the end of the project	July 2022	YES

E: PROJECT MANAGEMENT
Foreseen start date: July 2018 Actual start date: July 2018
Foreseen end date: December 2020 Actual (or anticipated) end date: July 2022

Activities undertaken and outputs achieved
This action comprised 3 tasks:
• E.1.1. Project Management
• E.1.2. After-Life Plan

E.1.1. Project Management
The management and control tasks of the project began with the launching of the project through the “kick off meeting” in July 2018 in REYDESA headquarter in Legutiano (Deliverable E.1.1. Minutes of Meeting). This meeting reviewed the objectives and structure of the project: work plan in general and the distribution of tasks, as well as the process of justification to be carried out during the project. Subsequently, a detailed technical workplan for each action for the different months and a general description of activities was explained. Once the technical part was completed, administrative and financial issues were addressed too.

On the other hand, the Project Management Plan (Deliverable E.1.2. Management Plan) was elaborated, which details the contents and structure of the project as well as the management procedure, general rules for justification, beneficiary financial statements, final audit, payment procedure, document management and project change procedure and potential problems. In addition, it describes partners roles and duties, as well as the technical and administrative meetings to be held and its periodicity. The tasks of monitoring and supervising the project are being carried out simultaneously to the execution processes of the project.

The meetings with the external monitoring team NEEMO, Ms Itxaso Mora, were carried out in:

- First monitoring visit June 2019, which analysed the technical and administrative progress of the project.
- Second monitoring visit in June 2020, which analysed the technical and administrative progress of the project and was held online due to the recent covid situation.
- Third monitoring visit in December 2021, which analysed the technical and administrative progress of the project.

Reports:

- Mid-Term report was sent in March 2020, which covers the project revision from July 2018 to December 2019. Due to the important changes presented in the Mid-Term report compared to the grant agreement, additional information was required in April-May 2020.
- Control report was presented in April 2021, updating the project info till March 2021.
- Control document was requested by NEEMO to understand the actions progression till May 2022.

Also, and amendment for an extension of the project was requested on October 2020, extending the project from December 2020 to July 2022.

The present final report must be presented in October 2022.

Green procurement Strategy:
The general objectives of this plan were the following:
• Promote the acquisition by the consortium of goods, works and services with the lowest possible environmental impact.
• Support with concrete measures to achieve smart, sustainable growth and integrator guaranteeing, at the same time, a more rational and economic use of public funds, both from the point of view of the investment and from the point of view of exploitation.
• It is also necessary to introduce selection criteria for entrepreneurs who have approved quality systems that can contribute to achieve a better environmental sustainability.
• The possibility of assessment of the long useful life of the purchase of inventoriable material and the rest of products and services, in detriment of those products with programmed obsolescence or short useful life, can be an appropriate instrument to be able to require manufacturers to declare or certify warranties of products with a sufficiently long useful life in each type of material or equipment.
• The incorporation of circularity criteria to improve the disposition of raw materials, mainly through secondary raw materials, should be carried out in application of the principle of hierarchy of waste that is promoted from the European regulations and the Spanish legal system.
• The contracting of goods and services adhered to a system of environmental certification, giving preference to Ecolabel and, in case of not having this distinctive for the good or service in particular, opting first for an ISO certification and ultimately, by an environmental product declaration.
• The hiring of those companies that have a system will be promoted of environmental management attached to the Community Eco-Management and Eco-Audit System, known as EMAS.
• The goods, services and products acquired have an impact on global warming, that is, have a carbon footprint associated. The management should strive to reduce its carbon footprint, and consequently, in acquire goods, services and products with the lowest possible carbon footprint calculated from comparable way.
• Impulse of the digital publications to increase sustainability and protection of the environment.
• Demonstration the innovation partnership between industry and SME, according to the procedure for establishing an innovation partnership set out in Article 31 of Directive 2014/24/EU. Where a contracting authority wishes to purchase goods or services, which are not currently available on the market, it may establish an innovation partnership with one or more partners. This allows for the research and development (R&D), piloting and subsequent purchase of a new product, service or work, by establishing a structured partnership.

Examples of achieved results inside the Green procurement strategy:
ECOINTEGRA – FUNDACION ASPACE
For the provision of raw materials, Reydesa has collaborated with the Aspace Navarra Foundation for employment (FANE), a non-profit foundation with CIF G31794654. FANE has a WEEE manual depollution facility called Ecointegra in Navarra, Spain; where WEEE belonging to categories 2, 3, 4, 5, 6, 7 and 9 are processed. (This is according to definitions applicable in Annex I of Spanish Royal Decree 110/2015, of February 20, regarding electrical and electronic equipment).As a result of this processing, Ecointegra separates various fractions of electronic printed circuit boards (PCBs), such as:
- Television boards. (Treatment result of category 4).
- PC Boards (Treatment result of category 3).
- Mixed Network Boards (Result of the treatment of the other categories).

Reydesa has a Legal Acceptance Document for this waste with Ecointegra; code EWC 160216, referenced DANP16010000568920160000497.
It has been decided to have this provider for BIOTAWEE project due to the environmental and social commitment of the FANE Foundation. To begin with, it is an entity of social economy and integration labour that works with people with functional diversity, especially with people with cerebral palsy. On the other hand, it is an entity with an environmental and sustainability commitment; having an environmental public policy, where the Foundation is undertaken to fulfil environmental requirements and establishes environmental objectives and goals that will be achieved through continuous improvement. To show the result of this policy, Ecointegra has got an ISO 14001 certificate since 2009; the certification was renewed under ISO 14001: 2015 norm on 11/14/2017.

In addition, as of April 1, 2016, the foundation obtained the WEEELabex private certificate, which guarantees excellence in the management of WEEE, for all the categories it deals with; including printed circuits that arrive to Reydesa. Ecointegra is currently inside the auditory procedure for renewing it.

OFFICE DEPOT
Office Depot is the official office material supplier for REYDESA and INATEC. The policy and criteria established is in accordance of the selected criteria for green procurement.

SCHARLAB
Scharlab is the supplier of chemicals used in the analysis lab in INATEC. Scharlab is committed to fulfil or exceed customer requirements by the implementation of a management system, which includes outstanding quality service and products, the preservation of environment and the assurance of the health & safety of the personnel. It has implemented since 1995 a quality system following the requirements of ISO 9000 and an environmental system since 2002 in the production unit according to the requirements of ISO 14000. Also, meets the requirements of the national law 31/95 about health & safety in job places.

E.1.2. After-Life Plan
After life plan it is available in digital format in the project website in 3 languages. The plan covers the following points:

- Project LIFE BIOTAWEE
- Achievements
- Exploitation plan
- Project continuation
- Project replication
- Future communication actions

<u>Deviations and main problems:</u>

The main problem of this action was the lack of fluidity on communications from BIOTATEC.

Milestone Name	Deadline	Achieved (Yes/No)
E.1.1 Kick-off meeting	July 2018	YES
E.1.2 Intermediate meeting	September 2019	YES
E.1.3 Final Meeting	July 2022	October 2022
E.1.4 Final report submitted with audit succeeded	October 2022	YES

Deliverable Name	Deadline	Achieved (Yes/No)
E.1.1 Kick-off meeting minutes	December 2018	YES
E.1.2 Management plan of the project	December 2018	YES
E.1.3 Report on green procurement strategy	June 2019	YES
E.1.4 Intermediate meeting minutes	September 2019	YES
E.1.5 After-life plan including an Exploitation plan	July 2022	YES
E.1.6 Project Audit	October 2022	Not applicable

6.2. Main deviations, problems and corrective actions implemented

The project started on July 2018 and the expected end date was December 2020. However, in October 2020, an amendment for the extension of the project was requested and final date for finishing the project was stated in July 2022.

First technical task developed has been **A1**. In this action, a **preliminary feasibility analysis** of the BiotaMet[4] technology was done to evaluate its use with WEEE. The feasibility study was performed with a selected waste stream from REYDESA's processes and finally, it has been stated that, in the current activity the applicability of consortium ARGCON5 for the use with PCB-s of WEEE was proved to enrich a methane producing microbial community from e-waste from REYDESA but not the metals recovery (Cu, Au and Ag).

On the view of this result, action **B1** was launched, with the aim of **optimization of specific parameters and microbial consortia of operation for bioleaching process**.
By the realization of the following laboratory experiments:

- anaerobic cultivation experiments (250mL-1L): anaerobiosis (argons gas) and neutral pH;
- aerobic cultivation experiments (250mL): shaking conditions and acidic pH;

experiments with aim to neutralize the remaining waste to better understand the behaviour of microbial consortia and to finally select the specific parameter for the application under study. These tests have been completed during the month of September 2020.

With the competition of previously mentioned tests, the bench scale tests (20L) have started on the first days of October. These last tests were expected to be completed by the end of October. During this time, the corresponding deliverables should have been completed. However, the recovery of information from BIOTATEC took longer, being the last results out of the task B2. During this process several problems happened. Mainly economical ant technical problems that have directly impacted in technical works carried out.

On the one hand, BIOTATEC has faced economic problems. The majority of BIOTATEC costs (82% of the budget) were planned to be generated during the first 12 months of the project, creating a lack of working capital. Unfortunately, BIOTATEC application for a loan in sum of 70 000 euros for a period until Mid-Payment for EC has not received a positive decision from credit institutions. Given lacking sum was going to generate debts to suppliers and workers, therefore the laboratory actions were made with minimum costs in order to avoid negative effect of bigger debts on the project.

Continuously a loan / investment was looked by BIOTATEC management. Agreement made with an investor on the 1st of September 2019 increased BIOTATEC working capital by 29,000 euros, allowing BIOTATEC to continue with all BIOTATEC projects. Additional working capital is being looked by management of BIOTATEC.

In the other hand, in relation to technical the following problems and consequently deviations took place:

[4] BiotaMet project (nº782070) titled "Feasibility study on nature based innovative more efficient 2-step bioleaching technology producing methane gas and metal compounds from low grade multimetallic European black shales or wastes containing organo-metallic complexes". By BIOTATEC

• The adaption period of microbial consortia for extracting Au and Ag from e-waste were longer than anticipated. Although consortia was adapted successfully to extract Cu, adaption of microbial consortia to extract Ag and Au is still being carried out for bench scale experiments, that has brought about extending of B1 and as a consequence delayed pursuivant action B2.

• In addition, the Covid-19 situation has also caused important delays in laboratory tasks. The Estonian Government declared a state of emergency on the 12th of March, resulting a pause in the everyday work in universities. Estonian citizens are advised to work from home, but sadly running biomining tests at scale of 20 Litres from home were not possible. BIOTATEC was and is renting laboratory premises from the University of Tartu and frozen the ongoing tests at that moment. The state of the emergency is declared until 1st of May. Even though, BIOTATEC workers stayed home longer time. This fact has directly impacted in already started tests, as most of them were abandoned, and the microbial consortias were lost.

• When the workers were able to return to work in the laboratory, they had to relaunch the tests that were abandoned in March. At the moment, cultivation experiments have recently finished and the bench scale (20 L) experiment of anaerobic phase, have just started in October 2020 and will run until the end of October 2020.

• Cu was extracted in aerobic phase as proposed and as described in previous reports. Based on the information given by 250 ml experiments, the calculations of pilot scale have been already done scaling only the aerobic phase. The received final data on Au and Ag, result for last tests on going, will not affect the principal construction of the pilot device.

The deviations mentioned have delayed the competition of tasks B1 and B2, and as direct consequence was pushing a deviation in the finalization date of the project. Based on the preliminary results of B1, B2. Pilot building started. The main objective of the action is the pilot building of the bioreactor which was carried out in REYDESA-INATEC's facilities.

This action included 3 tasks:
• B.2.1. Supply/sample preparation
• B.2.2. Pilot building and installation
• B.2.3. Set-up and operation

<table>
<tr><th></th><th colspan="6">2018</th><th colspan="12">2019</th><th colspan="12">2020</th><th colspan="12">2021</th></tr>
<tr><th></th><th>Jul</th><th>Aug</th><th>Sep</th><th>Oct</th><th>Nov</th><th>Dec</th><th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th><th>May</th><th>Jun</th><th>Jul</th><th>Aug</th><th>Sep</th><th>Oct</th><th>Nov</th><th>Dec</th><th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th><th>May</th><th>Jun</th><th>Jul</th><th>Aug</th><th>Sep</th><th>Oct</th><th>Nov</th><th>Dec</th><th>Jan</th><th>Feb</th><th>Mar</th><th>Apr</th><th>May</th><th>Jun</th><th>Jul</th><th>Aug</th><th>Sep</th><th>Oct</th><th>Nov</th><th>Dec</th></tr>
<tr><td>B2</td><td colspan="11"></td><td colspan="15">previous B2</td><td colspan="16"></td></tr>
<tr><td rowspan="3">update B2</td><td colspan="20">B2.1</td><td colspan="22"></td></tr>
<tr><td colspan="11"></td><td colspan="21">B2.2</td><td colspan="10"></td></tr>
<tr><td colspan="28"></td><td colspan="12">B2.3</td><td colspan="2"></td></tr>
</table>

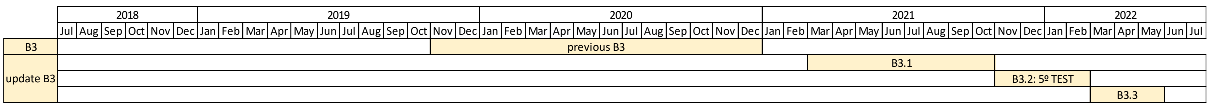
In B.2.1. Supply/sample preparation, as first step and an introduction to the action, a deep analysis was done on what PCB are, its composition, PCBs waste management, recycling technologies of printed circuit boards (physical and chemical recycling), and industrial application of PCB recycling. (the complete study in LIFE_BIOTAWEE_ B.2.2 Semi-industrial scale technical report). Action B.2.1 was started in July 2018 instead of June 2019. In 2018, the work done only comprises the purchase actions and in 2019, crushing and separation process of the material was proposed under action B2.1. Supply / Sample preparation which was concluded in February 2020.

In B.2.2. Pilot building and installation. The main objective of the action was the pilot building of the bioreactor which will be carried out in REYDESA-INATEC's. Based on the preliminary results of action B, this action was started with a design of a bioreactor for anaerobic and aerobic treatments. However, based on the results presented in Midterm report, regarding 250 ml experiments (the only ones finished) the design of the pilot plant suffered several changes as it was explained in the Midterm report and in the later required documents. So, finally, the design will only contemplate the aerobic step for the Cu recovery in a pilot plant of 50 l. The new design of the planned pilot plant was expected to be launched to providers in March 2020 and was expected to have it by the summer, along with the final results of action B1 in the 20 l reactors by BIOTATEC. However, the COVID-19 situation forced us to delay this task until the last week of June 2020. The Spanish government declared the state of alarm on 14th of March and REYDESA-INATEC'S workers were advised to work from home as much as they can. The government extend the state of alarm until 12th of April, reducing the companies allowed to continue with their activity only to the ones that may considered inside essential activities as is compiled in RD – Ley 10/2020 29th March. This will be the case of Reydesa, which has been included in essential activities regarding annex 18 of the RD-ley10/2020 29th March. At this stage, the staff in trying to contact by email with the previous selected suppliers to continue with the design of the reactor, however, until the date no answer has been received.

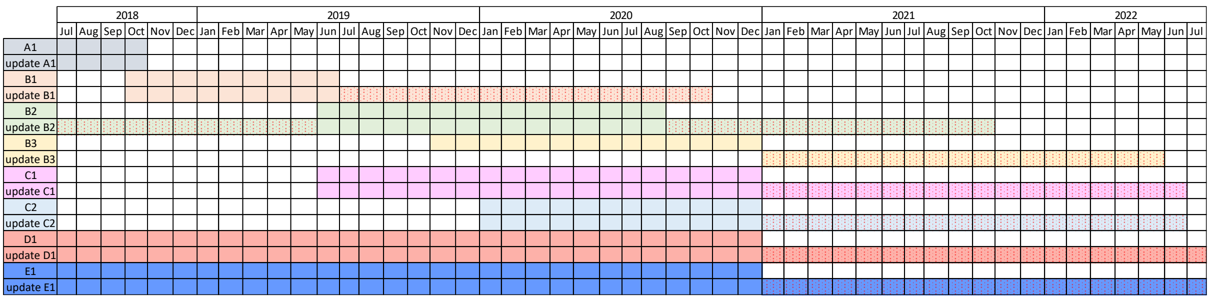
During the summer 2020, new contacts were done and some of the parameters were adjusted, due to the uncertainty of some needed controllers by the pilot plant. In the offers obtained the design was proposed as flexible as possible to overcome these uncertainties related to the unfinished action B1 in 20 l. Finally, the purchase was launched in the first months of 2021 and the complete equipment was built in September 2021.

B.2.3. Set-up and operation started in 2021 with the adaptation periods and with the scale up until 10L and 50L reactors were ready. In action B.2.3, was planned to do 4 complete tests in order to demonstrate the results showed by BIOTATEC in 250 ml experiments of action B1. As nor REYDESA neither INATEC have worked before with bioleaching technologies, we thought that the first experiment should need a training because of that the first experiment comprises 5 months instead of the 3. The planned 4 batches will be done in order to achieve reproducible and efficient leaching for Cu. These tests will be done using At. Ferrooxidans, the bacteria used until the date in aerobic phase by BIOTATEC.

Action B2.3. Set-up and operation was done along action **B3 Post processing**.



Finally, in relation to cross-cutting actions, due to the described delays, actions C1, C2 y D1 were delayed too. As a direct consequence actions C1, C2, D1 and E1 were extended until the end of the project. In the following images an update of project timetable is included.



6.3. Evaluation of Project Implementation

Please evaluate the following aspects of the project:

1. <u>Methodology</u> applied: discuss the successes and failures of the methodology applied, the results of the actions conducted and the cost-efficiency of actions.

In deliverable *B.3.2 Cost-effectiveness analysis* it is described the viability of the LIFE BIOTAWEE process on an industrial scale. This analysis is development in Action B3 (Post-processing).

It is based on the decision-making carried out throughout the technical development Actions (B1, B2 and B3) that identifies the most economically efficient way to achieve the set objectives in project.

This Action has been carried out by the PMC which has been formed by the technical managers in charge of the implementation of the different actions of the project, and chaired by the project coordinator in BIOTATEC, REYDESA (and INATEC).

Several temporary inflexion points have been chosen in the project execution schedule (along Actions B1, B2 and B3), where the PMC has made technical decisions (supported by technical, economic and environmental aspects) that have redirected the evolution of the project and have influenced the achievement of the objectives sought by the proposal.

The document contains the viability study of the process with the following point of analysis:
- Technical viability. The validity of the processes is analysed, trying to provide an aid in deciding which variables are technologically more viable, according to the quantity and quality of the products obtained in each case.
- Economic viability. An estimate of the cost of the processes considered will be made based on the data obtained in the tasks: consumption of reagents, quantity and quality of the metal obtained, energy consumption and waste generation.
- Environmental viability. Studies on environmental viability taking into account the generation of solid waste liquid effluents, emissions to the atmosphere or quantity of energy resources consumed is carried out.

<u>DECISION-MAKING BY PMC IN TEMPORARY INFLEXION POINTS</u>

After b1 action. conclusions presented at midterm

According to initial planning in LIFE-BIOTAWEE project, action B2 was planned as a scale up of the previous action B1, from 20 L to 200 L in order to analyse how the procedure works in a bigger scale. However, the results regarding the 20 L experiments from BIOTATEC, and REYDESA-INATEC base the planification for the following experiments on the results obtained and the parameters studied in the experiment performed by BIOTATEC in 250 ml. Regarding these results for the main objectives of the extraction procedure, REYDESA-INATEC considers implementing two changes in the planning presented:

- A. The pilot plant will consider only the aerobic phase in order to leach Cu from the non-metallic phase of PCBs.
- B. The pilot plant will be redesigned in a reactor of 50 l.

In the tests showed in action B1 (250 ml), the leaching of copper comparing the 2-step bioleaching technology (pre-treated material F15) with 1-step bioleaching (untreated material F15) was shown as to be equal paying attention to copper recovery.

REYDESA considers, on the one hand, if no further Cu content can be leached by using an anaerobic phase, it is not worthy to apply this pre-treatment before the aerobic phase. On the other hand, the conditions of the biogas obtained needs further steps in order to be commercialised so the dismiss of this step seems adequate based on the results given by BIOTATEC.

After b1 action. how to recover the precious metals contained?
Test carried out to date 31.03.2019 have shown that bacteria considered to carry out the building of LIFE-BIOTAWEE pilot are able to extract the copper contained in waste but don't extract the precious metals contained. The consortium proposes to test on laboratory-scale the bioleaching method, with different bacteria, to define the best final extraction method for precious metals. In Deliverable B.1.2. "Bench scale technical report", updated on 06.05.2022, tests carried out by BIOTATEC to respond to this topic are explained. Results of this trial (Experiment 4 aerobic phase using Chromobacterium violaceum) have served as the basis for the construction of the viability scenarios.

In b3 action. presented at deliverable b.3.1.
Three methods have been studied for metal extraction in B3 Activity (B.3.1 task):
- Fractional precipitation
- Copper cementation
- Electrowinning of copper

For bioleaching samples, electrowinning method is not technically feasible due to the low concentration of copper (less than 1 g/L in solution). Fractional precipitation and Cu Cementation are technically possible but Fractional precipitation consumes much more energy than cementation treatment.

After comparing both methods, the cementation method is chosen as the method for copper extraction. After recovering the copper by cementation, the fractional precipitation technique is applied to extract the aluminium and iron from the bioleaching sample. Therefore, copper is recovered by cementation in metallic form, iron in the form of iron oxide (III) and aluminium in the form of alumina.

2. Compare the <u>results</u> achieved against the objectives and expected results foreseen in the proposal and described in section 4: clearly assess whether the objectives were met and describe the successes and lessons learned. This could be presented in a table, which compares through quantitative and qualitative information the actions implemented in the frame of the project with the objectives and expected results in the revised proposal:

Action	Foreseen in the revised proposal	Achieved	Evaluation
B1, B2 and B3	Demonstration of a 2-step bioleaching technology in the recovery process of valuable metals from the non-metallic fraction of PCB of WEEE, that will also allow to produce methane gas through the application of an	Demonstration of 1-step bioleaching process to recover mainly Cu from the non-metallic fraction of PCB of WEEE. Cyanogenic bioleaching with Chromobacterium violaceum culture in aerobic bioleaching was performed in 20L reactor.	The aerobic process performed in 50L pilot plant, showed a recovery of 86 - 95% Cu and 1-4% Ag. Other metals contained in the waste in very low quantity have been also extracted with a recovery, around 76-88.5 % Al, 98% Zn or 53- 55% Ni.

	anaerobic process to the organic fractions.		Cyanogenic bioleaching. obtain a gold extraction of 44.7 %. Dicyanoaurate does not remain stable in solution with prolonged incubation times, so further optimisation is needed before scale up to 50L reactor
B2 and B3	Reduction in hazardous waste generation of 0.3 Tn at the end of the project respect a complete hydrometallurgical process	Both BIOTAWEE processes (1 step and 2 step aerobic) reach the proposed reduction in hazardous waste generation respect a complete hydrometallurgical process. 5 Tn of organic/aqueous solvents to be treated by 1Tn PCB vs 1.12 Tn /Tn PCB to be treated in 2 step aerobic bioleaching process, so 3.88 Tn waste management is reduced. The objective is accomplished, more than the 70% of hazardous waste is reduced (77.6 % of the effluents to be treated). According to solid waste, hydrometallurgy has 0.80 Tn vs 0 Tn to be treated. This is because the solid waste contained Au is fed into the second aerobic bioleaching and after this second bioleaching the solid waste does not contain hazardous metals so there is no need for treatment and can go to landfill or current possibility is to constructive industry. 5 Tn of organic/aqueous solvents to be treated by 1Tn PCB vs 0.62 Tn /Tn PCB to be treated in 1 step aerobic bioleaching process, so 4.38 Tn waste management is reduced. The objective is accomplished, more than the 70% of hazardous waste is reduced (87.6 % of the effluents to be treated). According to solid waste, hydrometallurgy has 0.80 Tn vs 0.33 Tn of 1-step. thus 58.75% of reduction.	The critical difference between biometallurgy and hydrometallurgy is the need in hydrometallurgy of using great quantities of organic solvents that has to be treated after the use. Moreover, the typical extraction stage used in hydrometallurgy as acid digestion. is non selective, base metals and precious metals are leached together, so after extraction there are several metals to be recovered and the complexity of the matrix and the solvents and stripping phases are multiple.
B2 and B3	Reduction 1,035 kWh electricity consumption respect hydrometallurgical processes at the end of the project	Biometallurgy (Cu. Al. Fe. Au) 2.477 (kwh/Ttreatment) Biometallurgy (Cu. Al. Fe) 1.23 8(kwh/Ttreatment) Hydrometallurgy (Cu. Al. Fe. Au) 331 (kwh/Ttreatment) To sum up, the biometallurgy process with 2 steps aerobic	This reduction was based in the impact of the generation of CH4 in the global consumption of the process. Since the generation of CH4 in the anaerobic phase for the treatment of non-metallic fraction of PCBs was not satisfactory. this reduction was not possible. The main advantage in hydrometallurgy vs

		bioleaching is 2,146 kwh/t PCB higher than the hydrometallurgical process and for 1 step aerobic bioleaching is 907 kwh/t PCB higher, due to the time residence for the biometallurgical processes and for the non-satisfactory generation of CH4 of the anaerobic bioleaching using non-metallic fraction of PCBs.	biometallurgy is the residence time of each experiment. In hydrometallurgy. the leaching in several hours may be done. however in biometallurgy the residence time is conditioned to the adaptation of the bacteria to the waste. If there are a population well adapted. the leaching may be done in 5 days in optimised conditions. The final data presented it was calculated using the optimised conditions premise and increasing the solid/liquid ratio to the maximum tested in BIOTAWEE process. 6%.
B2 and B3	Reduction 0.8 Tn CO_2 eq, emission respect hydrometallurgical processes at the end of the project	The reduction of CO_2 emissions respect hydrometallurgy is 0.798 Tn CO_2 eq, so it is practically achieved.	Based on the LCA: Pyrometallurgy: 1130 Kg CO_2 eq Hydrometallurgy: 1850 Kg CO_2 eq Biometallurgy (2-step aerobic bioleaching): 1052 Kg CO_2 eq More information about the LCA can be found in deliverable C.1.3.
B1, B2 and B3	Reduction 35-40% processing cost respect 1-step bioleaching processes	Final BIOTAWEE process is based on 1 step aerobic bioleaching process to extract base metals, mainly Cu. and can be completed adding a second step aerobic bioleaching process to extract precious metals. The estimation for reduction was based on BIOTATEC's knowledge from methane production given for 2-step bioleaching (anaerobic + aerobic). It was estimated that the methane generation will provide a reduction of 40 % in costs = 0.5€/Kg However. this estimation does not include parameters as: - solid/liquid ratio (supposed 10% solids into solution as the minimum). - the need of heat for anaerobic phase - The time required for the anaerobic phase - The need of additional 2 aerobic step to extract precious metals After the project, the proposed treatment for the non-metallic fraction of PCB using the	At the present time, the future for two step bioleaching should be found in wastes with lower particle size, for example the filter dust. However, inside the BIOTAWEE project, only one experiment was performed using the filter dust so the consortium does not have enough data to give an estimation of the reduction compared with the LIFE BIOTAWEE process of 1 step. Moreover, in order to extract precious metals, 2 steps aerobic bioleaching should be perform and in the initial proposal only 1 step was proposed for the metals recovery (Cu, Au and Ag).

		anaerobic phase is not efficient due to non-satisfactory generation of CH_4.	
B2 and B3	Reduction 50% processing cost respect a complete hydrometallurgical process	The reduction obtained is 38 % from 2-step aerobic bioleaching.	The hydrometallurgical process was estimated in 3,846 €/Tn from extrapolated data obtained in a research project performed by Reydesa-Inatec at lab scale. These data were very conservative because The biometallurgical (Cu, Al, Fe, Au) process was 2,372 €/Tn, 2-step aerobic bioleaching, data extrapolated from BIOTAWEE process performed by REYDESA at semi-industrial scale for the first aerobic step (a. ferroxidans) and extrapolated from BIOTAWEE process performed by BIOTATEC at lab scale for the second aerobic step (Ch. violaceum). The biometallurgical (Cu, Al, Fe, Au) was 1,192 €/Tn, 1-step aerobic bioleaching, data extrapolated from BIOTAWEE process performed by REYDESA at semi-industrial scale. The bioleaching process carried out in LIFE-BIOTAWEE project has been a selective process. For this reason, two bioleaching stages have been defined with two different types of bacteria (to extract the Cu. Fe and Al content and to extract the Au content). The price presented is result of mechanical treatment. two bioleaching treatments with operating conditions on a semi-industrial scale and metal extraction process. The viability of the process is strongly affected by the high consumption of reagents (not so much by waste management) and the low content of precious metals and copper.
B2 and B3	Recovery of 50 kg of value metals from each Tn of PCB treated.	182 kg Cu, 0.24 kg Ag and 0.021 kg Au	This is taking into account part of the copper recovered from the mechanical treatment. Other metals are obtained also, such as Ferric, hydroxides Fe

			and Al, however they are not targeted metals.
B1	Energetical recovery of 15.000 litres of methane from each Tn of PCB processed. The methane will be use in the Aluminum refineries of the OTUA Group, helping both in reduce the energetical cost and the industrial emissions of the process.	Not achieved. The methane generation was not satisfactory.	Using 1.5 g of PCB-s of WEEE (fraction F15 INITIAL) as a substrate within 120 days 71.95 ml of gas per g e-waste was released with methane content 23 to 50% (medium R2A + ARGCON5 + 1% e-waste). This was the best result and it was obtained at lab-scale. In bench scale it was not clear the methane generation in the experiments performed.
B1, B2 and B3	Reducing the volume of unused PCB of WEEE (non-metallic fractions containing organic compounds). Achieved	From 1Tn, 10% is NMF of PCB but there is algo another 30% of NMF, the suction dust.	Both waste go to landfill if no treatment is considered for them. So, with the proposed process this 40% can be treated.
B3	Evaluating the technological and economic possibilities in widening the usage of the innovative technology on other complex wastes with high content of plastic, in order to reduce processing costs (e.g. ELV or batteries).	To be technical and economically feasible, more than 17% Cu or 50 ppm Au has to contain the target waste. Other metals should be economically evaluated to present a proper analysis. In that sense, Reydesa will analyses the viability of a new project to extract Li from the LIBs inside the replicability actions.	More details in Deliverable B3.2 and B3.3.

3. Indicate which project results have been immediately visible and which results will only become apparent after a certain time period.

<u>Project results immediately visible:</u>
- Scale up to 50 L instead of 200 L due to the need of extra control of the bioleaching process.
- The possibility of cementation to recover metals. At the beginning, of the process (Task B.3.1) was thought as a better idea than the electrowinning which was the proposed one. This relays in the expertise of the lab team in other projects.
- The main objective of the anaerobic phase was the methane generation and not the improvements of the extraction of target metals.

<u>Project results visible after a certain time period:</u>
- The extraction of Au has to be done by other bacteria not with A. ferroxidans.
- The high selectivity of the bioleaching processes to leachate metals. This compared to hydrometallurgy may be an advantage because it is possible to recovers precious metals without the interference of base metals.
- The process to extract both base and precious metals, should have two sequential aerobic bioleachings.
- The adaptation will take longer times that the expected ones.
- The constrains in solid/liquid ratio in order to increase the production capacity.
- The importance of the pH in the bioleaching performances.

4. If relevant, clearly indicate how a project amendment led to the results achieved and what would have been different if the amendment had not been agreed upon.

The amendment for the extension was necessary due to the delay in action B1. If no extension was agreed, the project would not have been done in a semi-industrial scale.

5. Describe the results of the replication efforts.

The results obtained inside the LIFE BIOTAWEE project were very successful working with suction dust obtained in the mechanical treatment of WEEE, both for 2 step bioleaching anaerobic+aerobic and for 2 steps aerobic bioleaching.

After the project, the proposed treatment for the NMF of PCB using the anaerobic phase is not efficient due to non-satisfactory generation of CH4, however, when it was tested other waste as suction (zig-zag) dust from mechanical treatments the generation of biogas was improved. There main reason is that the particle size of zig-zag dust is smaller than that of PCB. The smaller particles provide larger specific surface area and thus both better contact for chemical reactions and availability for microorganisms. If the particle size diminishes, the probability of particles without metals increases and both become more readily available.

The carbon concentration in all fractions was similar - about 30% - which is good for methanogenesis. There have been papers published recently confirming the possibility of microbial degradation of epoxy resins. Altogether the number of papers on the biodegradation of epoxy resins is still moderate. Finally, with zig-zag dust the lag phase was 3.2 times shorter, confirming the better bioavailability of carbon as a result of finer structure of the material.

At the present time, the future for two step bioleaching should be found in wastes with lower particle size, for example the filter dust. However, inside the LIFE BIOTAWEE project, only one experiment was performed using the filter dust so the consortium does not have enough data to give an estimation of the reduction.

Another replicability possibilities:

- *Phosphogypsum (PG) residue*
- *Municipal Solid Waste (MSW)*
- *Bauxite Residue (BR)*
- *Lithium-ion batteries (LIBs)*

More details in the replicability deliverable.

6. Indicate the <u>effectiveness of the dissemination</u> activities and comment on any major drawbacks.

The project has a good feedback thanks to the webpage which provide us with useful information:

Figure 12. Data provided from the LIFE BIOTAWEE webpage.

The consortium performed several activities for dissemination of the project and in the following table the reached audience can be seen:

Table 3. Reached audience by each dissemination activity.

Webinar REYDESA	37
Webinar BIOTATEC	60
Charla Jon *UPV*	50
Visitas web	1456
the Second International *Oil Shale Conference (BAU-SIOSC)*	50
the European Research & Innovation Days session "*Walking the Talk"*	20
University of Basque Country	4
master's programme at KTH	1
Fennoscandian Exploration and Mining Conference	25
Raw Materials Week 2018 in Brussels	30
Cronimet	2
Fortech	4
PROMETIA	20
Biomining *'21, 7-10 June 2021*	20
Pitch presentation at the Raw Materials *Forum 23-24 May 2022*	20
Accelerating Materials Innovation program",	72
Wolves Summit in Vienna, October *2022,*	25
Batteries Event 2022	50
EIC Business Acceleration Services	20
Networking	4
Other *projects*	4
REYDESA + *INATEC PERSONNEL*	17

Biotatec	21
Futuro personnelindustrial *plant*	5

* Estimated value

This new innovative technology has been presented in conferences, dissemination and networking activities. In particular, two webinars were organized with the participation of NGOs, private companies, public bodies and individuals; at Estonian level in December 2021 by BIOTATEC, a webinar regarding electronic waste management; and at Spanish level, in July 2022 a webinar has been organized by REYDESA in collaboration with ACLIMA (Basque environmental cluster), with the participation of INATEC. Both webinars are available in YouTube, and also in the website of the BIOTAWEE project. After the both organised webinars, the interest strongly increase.

Results of LIFE BIOTAWEE are of great importance for the different policy makers at regional, national or European level. During the project, due to the workshops organized, and contacts that have been realized with the public government, 7 persons are calculated to be reached.

Regarding the private for profit, apart from the webinars, companies have been contacted by BIOTATEC, as part of PROMETIA association, as well as direct contacts with interested companies, and in the participation on innovation and acceleration services, reaching an estimated quantity of 116 companies.

For the individuals, taking into account the persons involved in the project (38), the networking activities during the project (83), website visits (1456), webinars and workshops organized by REYDESA and BIOTATEC (118), as well the participation in conferences and congress (194), the quantity reached is estimated to be 1889 persons.

The main drawback for the dissemination the COVID 19 restrictions have been.

7. Policy Impact:

<u>Describe project achievements which supported legislation (regional, national, EU)</u>

Taking into account the project obtained results, it can be concluded that the project LIFE BIOTAWEE is mainly related with the **Directive 2012/19/EU** on WEEE, helping to reach the minimum targets of recycling applicable by the recovery of metals from the printed circuit boards. In particular, the first step consists on the mechanical treatment, in which a 60% of metals are already recovered, obtaining streams with high content in copper, and also 10,2% of ferric scrap, that can be directly sold in order to be used in the production process in refineries or in steelmaking. In those copper refineries, the copper is completely recovered, by the production of cathodes mainly consumed to produce high-quality copper wire rod, that is later on processed and transformed into copper wire and cables, which final destination is primarily for electrical use. Based on this process, it can be estimated that 99% of copper is recovered from the streams sold after mechanical treatment. In this process, other metals are also recovered, like precious metals contained in the anode slime, that are sold to refineries specialized in processing this product to recover and refine the precious metals and other elements contained. The **Commission Regulation (EU) 715/2013** related to copper scrap End of Waste (EoW) and other EoW related to plastics is also accomplished, because the scrap is graded according to a customer specification or an industry specification or a standard for direct use in the production of metal substances or objects by smelters, refiners, re-melters or other metals producers. Nickel carbonate is produced in a precipitation process and used as the raw material to make nickel and catalysts for the petrochemical industry and as an additive in the glassmaking and ceramic industries. In the case of the ferric scrap, it is sold directly to steelmaking factories, mainly with Electric Arc Furnaces, in order to produce new ferric alloys with different applications. The rejected fraction from the mechanical treatment, with a lower copper content and without value in the actual market, is processed in the project by applying aerobic bioleaching, an 86 - 95% copper, 1-4% silver, 98% Zinc, 76-88.5% Al, 53- 55% nickel and 45 % gold can be recovered.

The Circular Economy has become one of the main strategies of the European Commission, who has adopted a Circular Economy Package and a specific **Circular Economy Action Plan**, whose implementation is being closely followed as can be seen in the “2015 Action Plan: Report on the implementation of the Circular Economy Action Plan”. Together with this report, the Commission also took further measures among which is proposed a targeted improvement of the legislation on certain hazardous substances in EEE. One of the objectives of this new legislation is to try to remove unnecessary barriers to secondary market operations, promoting a circular economy for the EEE sector in the EU.

According to the circular economy strategy of the Basque Country[5], the Basque economy imports 70% of its materials and, of the total consumption, 13% becomes waste. The industrial sector consumes 21 million tons of raw materials per year, of which 77% are imported, and, in fact, if more circular innovative solutions were undertaken, an achievable average potential saving of 6% of said consumption has been estimated of raw materials, which would mean savings of some 2,000 million euros in the Basque industry. The metal (steel, foundry, metal products) and mobility (automotive, aeronautical) sectors would accumulate half of the potential savings in Basque industry. For this and other reasons, the Diagnosis of the Circular Economy of the Basque Country[6] concludes that the industrial sector is seen as the pillar on which to articulate the transformation towards a more circular economy. This sector contributes almost 25% to the GDP of the Autonomous Community of the Basque Country, it is the most intensive sector in material consumption and waste generation and presents interesting opportunities for improvement. In the diagnosis of the circular economy of the Basque Country, the key metals are defined, which refer to the 27 critical materials defined by the European Commission and the main non-ferrous metals, among which is copper, among other metals such as aluminium, nickel, chromium, molybdenum, zinc and tin. The Basque Country consumes more than 187,000 tons/year of critical materials (European Commission List) for a value of €270 million/year and more than 472,000 tons/year of the main non-ferrous metals such as aluminium, copper, nickel, molybdenum, chrome, zinc and tin, copper representing 419 million €/yr. Therefore, this project aims to contribute to reducing supply risk in Basque industry and mitigating significant price fluctuations. It is a priority to reduce external dependency on the supply of copper and zinc by innovating in recycling processes and optimizing the management of metal scrap. In this project, 182 Kg Cu, 0.24 Kg Ag and 0.021 Kg Au are recovered from 1 ton of PCBs, helping to reduce external dependency of the supply, and increasing the local treatment of this waste generated in the decontamination of WEEE.

---

[5] Estrategia de Economía Circular de Euskadi 2030. https://www.ihobe.eus/publicaciones/estrategia-economia- circular-euskadi-2030-2

[6] Economía circular en la industria del País Vasco. http://www.ihobe.eus/publicaciones/economia-circular-en-industria-pais-vasco-diagnostico

Being the recovery and treatment of WEEE one of the main objectives of the LIFE Subprogramme, the project also faces another objective related to the Circular Economy by increasing the waste recycling rates and the valorisation of some by-products. LIFE BIOTAWEE will help to implement the circular economy concept by ensuring the use of secondary materials, as are the metals obtained from WEEE, in other industries or value chains. Related to Circular Economy and to the reduction of the energetical cost of the processes, it is important to indicate that in the anaerobic bioleaching process, as a result of the digestion process, methane is generated. Based on the results of methane formation, the application of the 2-step bioleaching technology to the non-metallic fraction of PCB showed modest results at laboratory level, but when scaling up this methodology, the methane formation was not noticed, and for this reason, it can be concluded that further optimizations steps are required for this waste. Despite this, during this project, its application to other type of waste, zigzag dust, has showed better results, indicating that its application could be successful for other type of waste. But, the application of the 2-step methodology to other waste, the dust produced in the mechanical treatment of PCBs, has been tested at bench scale and the results showed that it could be feasible for the treatment of other waste, with limited recovery with traditional treatments (if the Cu content is lower than 10% is landfilled, if it is higher, it is sent to pyrometallurgy, with its derived environmental impacts). Results of bioleaching solutions developed in the framework of LIFE BIOTAWEE project can and will be implemented to extract critical raw materials (such as for example light and heavy REE-s) from other types of industrial wastes. BIOTATEC has developed solutions for separation of metals from two industrial waste streams – bauxite residue (BR) and phosphogypsum (PG). BR is a leftover of Bayer process of alumina extraction from bauxite ore. It contains high amounts of iron (hence its colour by which it is colloquially known as red mud) along with many other metals, several of which are classified as critical raw materials, that include REE-s, especially scandium and other metals such as vanadium. The content of these metals is in the range of tens to hundreds ppm-s, but given the annual global BR production is more than 100 million tons, the amount of neodymium alone (a necessity for every electric car and wind turbine) is roughly on par with current global production. As a consequence of the presence of various metals of which several are toxic, BR is classified as hazardous waste. This effectively prohibits its uses other than depositing, which in turn creates a financial burden for mining/extraction operations. BIOTATEC has developed a technology for extraction of several critical raw materials from BR, especially scandium, vanadium and neodymium, exceeding 50% leaching ratios within a week with total extraction yields above 90%. In the process of extraction of these metals, other elements (e.g., arsenic) are being removed as well, converting BR into a non-hazardous waste.

PG is produced when phosphorus is extracted from phosphate ores with the help of sulfuric acid. In process up to 85% of the REE-s present in original phosphate rock is concentrated in the PG, making this material a rich source for various REE-s with concentrations as high as 5000 ppm-s. While there are many uses for gypsum in construction industry, the content of radionuclides, mainly in the form of uranium and thallium, forces it to be deposited just like BR. BIOTATEC's technology for extraction of REE-s from PG is capable of removing 70-90% of Ce, La, Nd, Pd, Sm, Eu, Gd in as short time as 6 hours. This means that with annual production of 300 million tons, large-scale implementation of BIOTATEC's technology would essentially satisfy global REE demand from PG alone, dramatically overhauling the geopolitics of resource control. As in the case of BR, our REE extraction technology also removes toxic elements, allowing "cleaned" PG to be inserted into circular economy, such as for example in road construction.

The knowhow gained during LIFE BIOTAWEEB project has helped to develop novel methods for converting these industrial waste streams to sources of critical raw materials and also to build pilot unit consisting of 100 L and 1000 L automated reactors This pilot unit allows to scale this technology and greatly facilitate the transfer of technology to industry-sized operations.
With the application of this technology to the recovery of critical raw materials, this project shows a very high synergy with the European Critical Raw materials act, and the communication COM (2020) 474 published as a result of the raw materials crisis derived from COVID-19. As part of the European Green Pact and the new industrial strategy for Europe; it is proposed to reinforce strategic autonomy; in a context where metals are a fundamental part of the ecological transition and the substitution of fossil fuels (decarbonization of the economy). The EU often relies on highly concentrated supply sources in a few third countries. This increases the EU's vulnerability to supply disruptions, leading to potential shortages and price hikes. The recycling and recovery rate of critical raw materials, essential to mitigate supply risks, is often close to zero and the quality of secondary raw materials is often low. With the BIOTAWEE project, a new technology in which the potential recovery of critical raw materials is possible has been successfully tested, and even when more research is required in order to scale up this technology at industrial scale, the results are promising. New technologies for recovery and treatment of wastes are included in the respective BAT, as it is indicated in the **Directive 2010/75/EU** related to industrial Emissions in the Waste Management Operations. In the future, when more robust results are obtained in bigger scale, this technology could be contemplated also in this document, as it has been proved that reduce the processing cost of 2 aerobic step bioleaching in a 38% and the hazardous effluents waste generation of 3.88 Tn/Tn PCB respect a complete hydrometallurgical process, reducing 42% CO_2 eq. compared with the hydrometallurgical process.

Additionally, this project supports the **Directive 2000/76/EC** related to Waste incineration, due to nowadays the final destination of the non-metallic fraction of the PCB of WEEE is to be incinerated in the facilities of copper refineries, without energy or material recovery so the implementation of the new solution will reduce the incineration of those products avoiding almost 300 Tn/ year of PCB only from the REYDESA's process.

Regarding the raw material part of the **H2020 Societal Challenge** 5 "Climate action, environment, resource efficiency and raw materials", it tries to tackle in a sustainable way the specific challenges outlined by the European Commission, maximising the economic and environmental benefits. The main focus of the raw materials part of this call is on securing the supply of minerals and metals through sustainable innovative production technologies for primary and secondary raw materials. This Challenge funds research and innovation with the following specific objectives:

- to achieve a resource – and water - efficient and climate change resilient economy and society, - the protection and sustainable management of natural resources and ecosystems, and
- a sustainable supply and use of raw materials, in order to meet the needs of a growing global population within the sustainable limits of the planet's natural resources and ecosystems.

The LIFE BIOTAWEE project is targeted at the focus area of sustainable use of raw materials which stresses the importance of developing and bringing to market cost-effective and resource-efficient technology solutions for the secure raw materials supply.

Moreover, in 2014 the EC has promoted **the EIT Raw Material, to** face as main challenges the sustainable exploration, extraction, processing, recycling and substitution. So, with those precedents, is clear that LIFE BIOTAWEE is straight aligned with some of the main environmental strategies promoted by the EU.

In the **Regulation (UE) 2019/1021,** the new restrictions are consistent with the ambitions of the European Green Deal to achieve toxic-free material cycles and with the new Circular Economy Action Plan. Even when at the moment these substances are forbidden, the material that is commonly treated in REYDESA facilities is post-consumption, which means that are equipment and components that may have more than 20 years since its fabrication, for this reason the presence of these substances mainly in the plastic fraction recovered of WEEE could be possible in the following years. This plastic fraction will have to be separated, and additional wastes will be generated, like fly ash, that depending on its composition, could be also treated with BIOTAWEE solutions. This is related also with RoHS Directive, that regulates on restriction of the use of certain hazardous substances in electrical and electronic equipment sets the rules restricting the use of hazardous substances in electrical and electronic equipment to protect the environment and public health.

<u>Indicate the main barriers identified and the action(s) undertaken to overcome them:</u>

The European Council's Versailles Declaration of March 2022 called to secure EU supply of critical raw materials, particularly by building on the strengths of the Single Market. Similarly, the European Parliament called for an EU strategy for critical raw materials in its November 2021 resolution. The REPowerEU communication and the Joint Communication on the Defence Investment Gaps Analysis and Way Forward announced in May 2022 that actions, including by legislative means, will strengthen EU resilience and security of supply of critical raw materials. Currently, recycling of CRMs is not economically attractive for CRMs other than palladium and, to a certain degree, cobalt and antimony under the present economic framework conditions. Additionally, the absence of clear requirements to recycle CRMs, the generic, weight-based collection and recycling targets for WEEE in the EU lead to producers and member states focusing on overall tonnages rather than the quality recycling of small amounts of CRMs. The European recycling industry is worried because this will make its processes much more expensive, and for this reason research will be needed to make the separation in an efficient way and need financing of recycling processes, if they become more expensive in order to maintain it economically feasible. In this project, a new technology that can be potentially used for recovery critical raw materials has been tested, but the quality of the products recovered are still under study. The main problem for the recovery of critical raw materials from WEEE is the lack of (detailed, quantitative) information and marking of key CRM components and their chemical composition; in order to avoid dilution with other materials, and increase the economic feasibility of the recovery of these materials.

The European List of Wastes (LoW) is the waste classification in the EU for administrative purposes, for permitting and supervision in the field of waste generation and management. The LoW defines 839 waste types which are structured into 20 chapters, mainly according to the source of the waste, like the economic sector or process of origin, and each waste type is characterised by a six-digit code. The allocation of wastes to the defined waste types is laid down in the introduction of Decision 2000/532/EC and explained in a separate section. In the commission decision of 18 December 2014, the list of waste pursuant to Directive 2008/98/EC is amended, being this the list of codes that are valid nowadays. In this list, the PCBs are classified as code 16 02 16 components removed from discarded equipment other than those mentioned in 16 02 15, that are the hazardous components removed from discarded equipment. This means that codified in this number, you can find a wide variety of different components removed from discarded equipment, being this code not descriptive enough to obtain information of content of PCBs or other components with CRM content. In occasions, some European members can define specific codes in order to be more specific in the management of certain streams, as it is the case in Spain when the list code is implemented in its own state regulations. This is very helpful in the management of waste within the state member, but this improvement is hinder when the waste is transferred to be managed outside, where that specific code is not valid. The solution would be the revision of this list of waste list, and include the best practices implemented in the rest of the state members, in order to improve the information obtained with this classification, and being able to track the CRM easily.

In particular, REYDESA participates in CircThread project, a H2020-LOW-CARBON-CIRCULAR-INDUSTRIES-2020 project whose main objective is to enable information exchanges by delivering a Circular Digital Thread methodology as a new information management framework and platform for facilitating information flows across the extended life cycle chain. Information about products and their components to improve understanding of Materials and Substances and related Circularity, Environmental, Social and Economic decision-making contexts. CircThread will provide for a Materials and Chemicals Identification, Tracing and Verification Services (MCTVS) across the life cycle using the Circular Digital Thread to obtain the entire flow of critical raw materials and chemicals along the life cycle of their products, detecting material losses and undesired chemicals. This project counts with three pilots, Italian, Spanish and Slovenian, each one focused on the life cycle of specific appliances, in particular, in the Italian Pilot Cluster the PCBs are included. With this new tool, more information of the location of CRM will be available, and is expected to increase the possibilities to increase its recovery.

Additionally, the Council on 25 of October 2022 has formally adopted a regulation to reduce the limit values for the presence of persistent organic pollutants such as PFOAs or PBDEs in waste, with the aim that these toxic substances do not enter the recycling cycle. The Regulation mainly affects brominated flame retardants, that are present in plastics contained in WEEE. Even when, since this regulation is put into force these substances will be forbidden, the material that is commonly treated in REYDESA facilities is post-consumption, which means that are equipment and components that may have more than 20 years since its fabrication, which means that the presence of these substances mainly in the plastic fraction recovered of WEEE is more than possible in the following years. Requirements to separate this component could jeopardize the recyclability percentages of WEEE, as all plastic containing this substance will need to be eliminated. Apart from this, the legislation is focusing on specific substances, that are not currently analysed in such detail, and this means that a higher effort has to be performed in order to accomplish with this requirement. Some efforts have been performed in Otua Group, in order to evaluate different technologies to separate the bromine flame retardant plastics from the other ones in specific research projects, with good results, but more effort would be required for increasing the selectivity of this separation.

In the usual treatment of WEEE, when an equipment at its end-of-life is received complete in the treatment facilities, the decontamination has to take place before shredding. In this decontamination, the PCB and other components that the legislation defines have to be recovered previous to shredding, but apart from that, in the complex solid waste streams received, the PCB can be also found. REYDESA has invested in a specific plant that is able to detect and separate the PCB from a complex solid waste stream, making possible to separate the PCB from the input streams, increasing the recovery of this waste. But due to its lead content, REYDESA is not authorized to treat them, as specific equipment is required to obtain the environmental authorization. But apart from that, only the mechanical treatment has been proved that is not feasible, and a 40% of the waste input is obtained as rejected fraction. BIOTAWEE project was focused on recovery metals from this rejected fraction, increasing the overall economic feasibility of its treatment, but specific conditions have to be met in the input waste in order to be feasible at industrial scale. In particular, it was estimated in the cost-effectiveness deliverable that, it would be economically feasible when the non-metallic fraction of PCB contains a percentage of Cu greater than 17% or Au greater than 50ppm.

Apart from this, some estimations had to be made in order to reduce not only the cost of the process, as well as the overall feasibility of this solution. The first optimization was that, although washing stage is a common treatment in bioleaching processes, in order to evaluate results of the global process with and without washing stage, were carried out specific tests in REYDESA(INATEC) laboratory (see Deliverable B.2.2). Due to the high amount of water consumed during this stage and the lack of improvement in technical results having used a waste wash, the washed stage is ruled out in the definition of the process. This helps to reduce the environmental impact of the overall process, to reduce the quantity of effluents generated, and to increase the economic feasibility of the process.

The alternative BIOTAWEE requires a long process time, which could be improved with microorganism optimization tasks (better adaptation; better control of feeding and pH conditions). Additionally, it is estimated that the BIOTAWEE alternative will works in a solid:liquid ratio of 6%, and for implementing this at industrial scale, tests would be needed to increase the solid:liquid ratio with a view to increasing production capacity and minimizing effluents generated.

Apart from these estimations, BIOTAWEE process has been also analysed in detail, in order to evaluate the main impacts of each step, and, in all the cases, the main impacts are Climate change and Energy resources – fossil fuels; being the lower impacts human toxicity carcinogenic and no carcinogenic, land use and ozone depletion. In the mechanical treatment, the main impact is energy resources – fossil fuels due to the electric energy consumption of this step is the main contribution to its impacts, apart from the dust generation. In the case of the bioleaching steps the energy consumption is greater than the one estimated in the mechanical treatment, due to requiring of heat and agitation during long periods of time. This situation, in conjunction with the high consumption of chemical reagents for the preparation of the medium, produces that the main impacts of these steps are climate change, energy resources – fossil fuels and Ecotoxicity freshwater. In the step of metallic extraction, the consumption of high quantities of sodium hydroxide, and the requirement of heat, produces that the main impacts of these steps are climate change, energy resources – fossil fuels and Ecotoxicity freshwater. In order to reduce the overall impact of BIOTAWEE process, electric energy consumption of bioleaching processes should be reduced, effluents should be reused to a more extent and the use of reagents in the metallic extraction should be reduced. Even taking into account that, it should be outlined that BIOTAWEE option has always lower impact than pyrometallurgy, and also with hydrometallurgy, defined as mechanical treatment followed by chemical leaching.

6.4.Analysis of benefits

In this section please discuss the project's progress focusing on the results achieved. Justify any anticipated significant deviations from the targets set initially, and comment on targets already met or exceeded. In the case of the Final report, where relevant, refer to the final actual values of the Key Project-level Indicators(KPIs):

1. Environmental benefits

a. Direct / quantitative environmental benefits:

The main environmental benefits obtained in LIFE BIOTAWEE project are described below:

- *Reduce the volume of unused fractions of PCB.* From 1 Tn of PCBs, 10 % is NMF of PCB, initially named as impurities and the primary objective of the present project. However, during the project it was also found another fraction to be considered as NMF and which currently has not an efficient treatment: This new fraction is the suction dust from the mechanical treatment which is the 30 % approximately of PCBs. The project has demonstrated the technical feasibility of this recovery so the perspectives are really interesting in this regard.

- *Reduction in hazardous effluents waste generation of 3.88 Tn/Tn PCB respect a complete hydrometallurgical process.*

Table 4. Waste generated comparative,2 aerobic Biometallurgy vs Hidrometallurgy.

Treatment	**Waste generated to treatment (T/T treatment)**		**Waste generated to reuse (T/T treatment)**	
	Solid	**Aqueous**	**Solid**	**Aqueous**
Biometallurgy (Cu, Al, Fe, Au)	0.00	1.12	0.28	3.51
	1.12		3.79	
Hydrometallurgy (Cu, Al, Fe, Au)	0.80	5.00	0.00	0.00
	5.80		0.00	

Biometallurgy (Cu. Al. Fe. Au): 2-step aerobic bioleaching. data calculated from BIOTAWEE process performed by REYDESA at semi-industrial scale for the first aerobic step (a. ferroxidans) and extrapolated from BIOTAWEE process performed by BIOTATEC at lab scale for the second aerobic step (Ch. violaceum).
Hydrometallurgical data is extrapolated using the data obtained in research project performed by Reydesa-Inatec at lab scale. The data of waste generation is very conservative.

The critical difference between biometallurgy and hydrometallurgy is the need in hydrometallurgy of using great quantities of organic solvents that have to be treated after their use. Moreover, the typical extraction stage used in hydrometallurgy as acid digestion, is non selective. base metals and precious metals are leached together, so after extraction there are several metals to be recovered and the complexity of the matrix and the solvents and stripping phases are multiple.

The waste generated to be reused is divided into solid and liquid. The solid has been analysed and its characterisation shows that may have constructive applications or at final term may go to a regular landfill. The liquid phase may be reused in the actual process but inside the project no test was made with reused medium. The analysis made to the liquid phase showed that the metal concentration do not exceed the maximum levels for metals in order to be discharged to the water collector.

The management of hazardous wastes could be between 65 € - 120 € / Tn depending of the treatment.

- *Reduce 45 % CO_2 eq compared with the hydrometallurgical process*.

Table 5. Summary of results of the total impact of the life cycle of the equipment in the study, with the impact categories of single score and climate change.

Impact category	Unit	Pyrometallurgy	Hydrometallurgy	BIOTAWEE
Climate change - global warming potential (GWP100)	kg CO2-Eq	1.13E+03	1.85E+03	1.08E+03

In the global computation, the environmental reduction offered by the BIOTAWEE technique is evident, followed by the hydrometallurgical treatment, being the worst option pyrometallurgy. A detailed description of the data and the comparison made can be found in the *deliverable C.1.3 LCA.*

The impact categories that have the most significance in the impact of the treatments are climate change, ecotoxicity in freshwater, Energy resources - fossil fuels and material resources- metals/minerals. For pyrometallurgy, the most important impact is climate change, with a contribution of 39.45%, in hydrometallurgy and BIOTAWEE process, material resources-metals/minerals is the category with a higher contribution to the global impact, obtaining a 54.28% and 28.46% respectively.

This is due to the high quantity of reagents required for the hydrometallurgical and BIOTAWEE treatments, compared with pyrometallurgy, that requires of more energy.

One of the most important aspects to highlight in the comparison of processes is the logistics aspect. Considering that the pyrometallurgical process is carried out in Germany, the impact associated with the transport of the PCBs to the plant is considerable. In this aspect, carrying out a sensitivity analysis of the distance travelled by the printed circuit boards from the collection point to the processing/treatment plant, it is concluded that: the pyrometallurgical treatment of PCBs shows a more favourable environmental behaviour than the technique of hydrometallurgy, as long as the distance from the origin to the plant is less than 200 km.

But it could be also be concluded that even reducing the distance to zero, the Pyrometallurgical process will never show less impact than the BIOTAWEE process. In short, the environmental performance of the processes is closely related to two important aspects: on the one hand, the different product outputs for techniques; on the other hand, the relevance of the distance to the management company. These two variables influence the results, being decisive in the environmental comparison of both processes. Therefore, both aspects will be key in identifying the most recommended process.

- Avoid the incineration of *almost 300 Tn/ year of PCB only from the REYDESA's process.*

Nowadays, PCBs are incinerated in copper refineries because there is not a cost-effective method able to recover the metals. Approximately, REYDESA manages 300 Tn/year of PCBs from WEEEs annually and the 100% of them are sent outside to be treated through pyrometallurgy. This indicator is focused on the availability to increase the in-house management of this waste, with a technologically, economically and environmentally viable process. With this new process, the metallic fraction (which represents 60% of the total amount) is fully recovered in the mechanical treatment, and the resulting non-metallic fraction of PCBs could be recycled with the innovative bioleaching technology. Taking into account the economic viability of the project, the expected quantity of PCBs to be treated beyond 3 years of the project in order to make the process viable will reach 900 tons per year, but only 300 tons are generated in REYDESA, the rest of PCBs will have to be purchased in order to reach that quantity. During the project, 27.51 tons of PCB are treated, reducing the quantity to be sent outside to 872.49 tons.

- *Materials were recovered per Tn of PCB applying 2 aerobic bioleaching processes:*

    - 182 Kg Cu
    - 0.24 Kg Ag
    - 0.021 Kg Au

This recovery may be improved due to the optimisation need for the recovery of precious metals. The recovery for Au is stated in 45% and for the Ag 1-4%. So, there is room for improvement.

b. Qualitative environmental benefits

The main qualitative environmental benefits obtained in LIFE BIOTAWEE project are listed below:

- Bioleaching is more environmentally friendly comparing to the use of solvents needed in hydrometallurgy.

- Replicability: LIFE-BIOTAWEE process may treat the suction dust obtained from the mechanical treatment of other WEEE in REYDESA and in other companies of the recycling sector

- Promoting the use of biotechnology in the recycling process, contributing to make the recycling sector a “bio-based industry”.

2. Economic benefits (e.g. cost savings and/or business opportunities with new technology etc., regional development, cost reductions or revenues in other sectors); state the number of full time equivalent (FTE) jobs created, showing a breakdown in qualified/non-qualified staff.

LIFE BIOTAWEE process (using 2 aerobic step bioleaching process) reduce 38 % the processing cost compared to hydrometallurgical process.

The hydrometallurgical process was estimated in 3,846 €/Tn from extrapolated data obtained in a research project performed by Reydesa-Inatec at lab scale.

The biometallurgical (Cu, Al, Fe, Au) process was 2,372 €/Tn, 2-step aerobic bioleaching, data extrapolated from BIOTAWEE process performed by REYDESA at semi-industrial scale for the first aerobic step (a. ferroxidans) and extrapolated from BIOTAWEE process performed by BIOTATEC at lab scale for the second aerobic step (Ch. violaceum).

The biometallurgical (Cu, Al, Fe, Au) was 1,192 €/Tn, 1-step aerobic bioleaching, data extrapolated from BIOTAWEE process performed by REYDESA at semi-industrial scale.

The bioleaching process carried out in LIFE BIOTAWEE project has been a selective process. For this reason. two bioleaching stages have been defined with two different types of bacteria (to extract the Cu. Fe and Al content and to extract the Au content). The price presented is the result of mechanical treatment, two bioleaching treatments with operating conditions on a semi-industrial scale and metal extraction process.

The viability of the process is strongly affected by the high consumption of reagents (not so much by waste management) and the low content of precious metals and copper. The result of the accounts presented in *deliverable B.3.2 Cost-effectivenss analysis*, is highly dependent on the nature of the PCBs to be treated (metal content of the non-metallic fraction generated during the mechanical treatment of PCB). The scenarios that make LIFE BIOTAWEE process economically viable are presented below.

Table 6. Scenarios that make LIFE BIOTAWEE process economically viable.

Metalic Content	Productive Capacity (T/y)	Investment (€)	Energy Cost (€/Ttreatment)	Cost process (€/Ttreatment)	Valorization (€/Ttreatment)	Reagent consumption (€/Ttreatment)	Waste generated (€/Ttreatment)	Added Value Company (€/y)
50ppm Au	121	1.132.383	322	1.909	2.538	1.324	73	434.726
17% Cu	121	1.132.383	322	1.906	2.521	1.324	73	412.871

When the non-metallic fraction of PCB contains a percentage of Cu greater than 17% or Au greater than 50ppm, LIFE-BIOTAWEE process begins to be economically viable. This would mean considering mixtures of PCB qualities where the percentages Type 1/A/High quality PCB was greater than 80%.

In this case, the expense and revenue accounts are presented in Table 7. Under these conditions, the return of capital to the company is achieve in 2.7 years from the third year in operation. At that time, the process generates an added value of 412k€ per year for the company.

Table 7. The expense and revenue accounts considering a scenario that make LIFE BIOTAWEE process economically viable

EXPENSE CLASSIFICATION

	2.023	2.024	2.025	2.026	2.027
Total sales	588.114	1.146.678	1.720.016	1.720.016	1.720.016
Nationals	411.680	802.674	1.204.011	1.204.011	1.204.011
Export	176.434	344.003	516.005	516.005	516.005
Net variation of Stock PT (in progress and completed)	0	0	0	0	0
Work made by emp. For your immobilized	0	0	0	0	0
Other income	0	0	0	0	0

Operating subsidies	0	0	0	0	0
Other income	0	0	0	0	0
TOTAL INCOME	**588.114**	**1.146.678**	**1.720.016**	**1.720.016**	**1.720.016**
Raw Materials Consumption	380.100	760.200	1.140.300	1.140.300	1.140.300
Buy MP	380.100	760.200	1.140.300	1.140.300	1.140.300
Net change in MP inventories	0	0	0	0	0
Personal expenses	90.000	181.800	275.427	278.181	280.963
Salaries	85.020	171.841	260.488	263.243	266.024
Social charges	4.980	9.959	14.939	14.939	14.939
Asset depreciation provision	113.229	113.229	113.229	113.229	113.229
Other operating expenses	435.863	871.430	1.307.146	1.307.146	1.307.146
Other variable manufacturing expenses	49.882	99.764	149.645	149.645	149.645
Other proportional selling expenses	5.881	11.467	17.200	17.200	17.200
Fixed selling expenses	0	0	0	0	0
TOTAL SPENDS	**639.092**	**1.166.459**	**1.695.801**	**1.698.556**	**1.701.338**
RESULT OF EXPLOTATION	**-50.978**	**-19.782**	**24.215**	**21.461**	**18.679**
Financial expenses	16.984	16.984	16.984	16.984	16.984
For comercial operations	0	0	0	0	0
For credit operations	16.984	16.984	16.984	16.984	16.984
Finance income-(expense)	0	0	0	0	0
Income-(expenses) for Exchange differences	0	0	0	0	0
ACTIVITY RESULT	**-67.962**	**-36.766**	**7.230**	**4.476**	**1.694**
Extraordinary results	0	0	0	0	0
Amortization of capital grants	0	0	0	0	0
Extraordinary income-(expenses)	0	0	0	0	0
RESULT BEFORE TAXES	**-67.962**	**-36.766**	**7.230**	**4.476**	**1.694**
Corporation tax	0	0	0	0	0
RESULT OF THE EXCERSICE	**-67.962**	**-36.766**	**7.230**	**4.476**	**1.694**
Dividend distribution	0	0	0	0	0
RESULT AFTER IMP. AND DIV.	**-67.962**	**-36.766**	**7.230**	**4.476**	**1.694**
CASH-FLOW	**45.267**	**76.463**	**120.459**	**117.705**	**114.923**
ADDED VALUE OF THE COMPANY	**152.251**	**275.247**	**412.871**	**412.871**	**412.871**

PCB management service within the recycling industry is not common. In cases where the recycling industry treats PCB fractions, the process usually begins with a mechanical treatment to recover the fractions with the highest economic value, but it generates a non-metallic fraction that is difficult to manage, such as the one used in the LIFE BIOTAWEE pilot.

The LIFE BIOTAWEE service has been defined to recover metal content in difficult-to-treat waste. The waste treatment service is offered whenever there is a content of

- >17% Cu or
- >50ppm Au

The service as defined can treat up to 304 Ton waste per year (6% of all PCBs collected in Spain in 2022) and costs 140€ per Ton.

At the end of the project 1 FTE job has been created in REYDESA, and another 1 in BIOTATEC, both with technical background. Beyond three years this quantity will increase till 10 FTE jobs generated, 5 by each entity. This is estimated based on the installation of an industrial plant, taking into account that 4 operators and 1 controller have to be hired for the plant, as well as new people to be part of the team of BIOTATEC.

3. Social benefits (e.g. positive effects on employment, health, ethnic integration, equality and other socio-economic impact etc.).

The main indicator for humans (to be) influenced by the project comes from the dissemination activities on the one hand, in which persons are concerned by the project independent of the project area, being the overarching context the countries of the partners; and on the other hand, the application of a new process with an innovative technology affects the persons regularly present in the project area, selecting as overarching context the location in which this project takes place.

In this calculation, for persons with improved capacity or knowledge due to project actions, the personnel involved in the project, from BIOTATEC and REYDESA, have been taken into account for the value at the end of the project (17 persons from REYDESA & INATEC and 21 from BIOTATEC). The number of persons will increase 3 years after the project end, due to the industrial installation of the process, in which 4 persons would be hired, and another 2 will be involved in the process. Additionally, it is expected that from BIOTATEC side, due to its continuation on the bioleaching field expertise, its experience in BIOTAWEE will generate another 6 persons with improved knowledge due to project actions.

Regarding the persons who may have been influenced via dissemination or awareness raising project-actions, the calculations take into account the dissemination activities performed during the project, like: development of notice boards, project brochure, Layman´s report, dissemination in press, participation in congresses, workshops and technical publications. Additionally, the main tool to disseminate this project is considered to be the project website, designed and implemented to achieve proper communication of the project, available in English, Estonian and Spanish. This value includes the website visits, 1456; the persons attending the workshops organized by BIOTATEC and REYDESA, 147; conferences and congress, 288 (estimated); and the networking activities, 83.

Beyond 3 years after the project end this quantity is expected to increase, due to the development of the Layman´s report, and the technical publications that are under revision at the moment, and the maintenance of the website, among the other dissemination actions performed.

4. Replicability, transferability, cooperation: Potential for technical and commercial application (transferability, economic feasibility - bankability, limiting factors, suitability for additional funding from other streams e.g. structural funds, EIB financial instruments, venture capitals, pension funds, responsible investors) including cost-

effectiveness compared to other solutions, benefits for stakeholders, drivers and obstacles for transfer, market conditions, pressure from the public, potential degree of geographical dispersion, specific target group information, high project visibility (eye-catchers), potential for replication in same and other sectors at the local and EU levels, etc. State the project's likelihood of replication (high/low/zero), and if its replication is market-driven or policy-dependant. Specification of potential market/replication vehicles. Possibilities for complementarity with existing market players and/or other solutions/projects (bundling). Those projects who have completed the C2M checklist or engaged in the Close-2-Market (C2M) Initiative should elaborate here on all the relevant C2M aspects. Those projects should also complete, by the Final Report submission stage, the final C2M checklist provided to them by the C2M experts.

Replicability: inside the project

After the results obtained in LIFE-BIOTAWEE process, the consortium put the focus on another problematic waste stream, suction dust. This residue is the filter dust collected in the suction system of the equipment dedicated to crushing and separating WEEE in the different material streams. This waste is mainly destined to Germany for its recovery in huge refining furnaces in the waste management industry, but it is only accepted when its Cu content is higher than 10%, and depending on the content of other metals like gold, silver or lead. In the case there are not accepted, the only option is landfill or being reintroduced in the process, when the metallic content may be refined. In fact, due to lead content of this waste, the recovery option in Germany has been jeopardized, and searching another type of treatment is required for this waste. In each mechanical treatment, depending on the material being processed, the composition of the filter dust may change so Acidithiobacillus Ferroxidans should be able to adapt to different composition ranges of the waste.

In order to have a wider information about the replicability of LIFE BIOTAWEE process to treat this waste, two tests were performed using 2 different suction dust. On the one hand, the consortium agreed to give another opportunity to the anaerobic bioleaching using suction dust due to its properties (more appropriate grain size and organic material) compared to NMF of PCBs. On the other hand, current conditions of LIFE BIOTAWEE process were tested in the semi-industrial pilot plant.

The consortium was highly satisfied with the conclusions of the tests performed. So the applicability of the methods were demonstrated.

Replicability possibilities which have been recently explored by BIOTATEC were:

Phosphogypsum (PG) residue:

The knowhow gained during BiotaWEE project has helped us to develop novel methods for converting these industrial waste streams to sources of critical raw materials. BiotaTec's technology for extraction of REE-s from PG is capable of removing 70-90% of Ce, La, Nd, Pd, Sm, Eu, Gd in as short time as 6 hours.

Bauxite Residue (BR):

BR is a leftover of Bayer process of alumina extraction from bauxite ore. It contains high amounts of iron (hence its color by which it is colloquially known as red mud) along with many other metals, several of which are classified as critical raw materials. These include REE-s, especially scandium and other metals such as vanadium. The content of these metals is in the range of tens to hundreds ppm-s, but given the annual global BR production is more than 100 million tons, the amount of neodymium alone (a necessity for every electric car and wind turbine) is roughly on par with current global production.

Replicability possibilities which have been recently explored by REYDESA were:

Lithium-ion batteries (LIBs):
Over the next three years, REYDESA and INATEC will participate in a basic research project to study the extraction of lithium contained in the black mass generated in the mechanical treatments of lithium-ion batteries at the end of their useful life.

The project brings together a total of 31 initiatives structured around three axes; decarbonization, connectivity and mobility as a service. In the field of decarbonisation, initiatives related to hydrogen, carbon-neutral fuels, batteries or the reduction of the weight of materials, among others, are included. Regarding the second axis -connectivity- different initiatives related to digitization, cybersecurity, the development of electronic vehicle platforms or connectivity will be addressed. Likewise, in terms of the axis of mobility as a service, new technologies will be developed that allow vehicles to be equipped with of innovative features.

The Group is made up of fifty companies that cover all areas of the future industrial ecosystem, technology companies, clean energy, circular economy, artificial intelligence, cybersecurity, services, vehicle manufacturing, components and batteries. Likewise, there are universities and technology centers, promoting public-private collaboration. The Budget for this action: 900,249.27 €

Environmental Objectives that will cover this replicability option:

- Contribute with this project to exceed the objectives proposed in the new draft of the European Commission (COM(2020) 798/3), of the Battery Regulation where it is established that, by 2025, all recycling processes must reach certain rates of recovery of 35% Li, having to reach 70% by 2030.

- Reduce the environmental impacts derived from metal recovery through traditional methods, which have a high impact and obtain a very limited recovery percentage of Li.

- Decoupling between economic growth and the generation of environmental impacts, by increasing the recovery percentage of Li.

- Contribution to the transition towards a Li consumption model. more circular and with a higher added value

The project has been submitted (and accepted) to the call of "Strategic Project for the Recovery and Economic Transformation (PERTE) of the Electric and Connected Vehicle" of the Ministry of Industry of the Government of Spain.

5. Best Practice lessons: briefly describe the best practice measures used and if any changes in the strategy employed could lead to possible adjustment of the best practices.

The communication between partners had suffered ups and downs along the project. At the beginning, the communication got along well, however in 2019 declined a little bit and added to the covid situation, the information flow was not adequate. In order to redirect the situation, the consortium had to reconsider how implement a better communication. So, the implementation monthly meetings to follow up the project was made.

Reydesa and Inatec implement the following actions to cover activities inside B2 and B3:

- Know the hazard of the substances and correct handling
- PPE and implementation of protocols for handling large amounts of acids (
- Sampling coding
- Procedures performance for the LIFE BIOTAWEE process
- Exhaustive cleaning of material/lab

6. Innovation and demonstration value: Describe the level of innovation, demonstration value added by EU funding at the national and international levels (including technology, processes, methods & tools, nature management methods, models for stakeholder involvement, land stewardship models, organisational & co-operational aspects).

Due to being the aerobic microorganisms used in the project already commercialised, in particular A. ferroxidans, A. thioxidans and C. violaceum, there has been not considered at this point any patent about them. However, the application of aerobic bioleaching using A. ferroxidans to the NMF of PCBs is an advance in the state of the art of bioleaching processes mainly because of the waste of application and the scale of application. Despite the fact that A. ferroxidans are commercial bacteria, the adaptation process increasing the solid/liquid ratio to 6%, the optimised operational conditions and the application to the NMF are a progress on what is published on literature. The publications related to PCBs, are mainly focused on the globality of the waste, the bioleaching process is applied to the PCBs itself not to the non-metallic fraction because the total composition is higher and the yield may be better.

PCB management service, as the one proposed in the project, within the recycling industry is not common. In cases where the recycling industry treats PCB fractions, the process usually begins with a mechanical treatment to recover the fractions with the highest economic value, but it generates a non-metallic fraction that is difficult to manage, such as the one used in the LIFE BIOTAWEE pilot. Moreover, the application of aerobic bioleachings to treat the suction dust from mechanical treatment is another advance that has been demonstrated in the present project.

Related to the treatment of suction dust, LIFE BIOTAWEE project demonstrate the possible application of an innovative more efficient 2-step bioleaching technology, combining aerobic and anaerobic treatment, with the generation of methane. The anaerobic technology developed by BIOTATEC has a patent already under revision entitled “Method for decomposition of the metallorganic matter of graptolite argillite by microbial consortium”. BIOTATEC has developed a know-how for recovering valuable metals in lab conditions in a 20L bioreactor system from the NMF(suction dust) of the PCB by the application of 2-step bioleaching technology, combining aerobic and anaerobic treatment. Based on the anaerobic experiments with PCBs of WEEE in 20 L reactor, amendments were made to the patent pending EP3416759.

Finally, it should be noted that thanks to the grant obtained in LIFE BIOTAWEE project, the scale up of the technology was possible and the feasibility of the proposal was demonstrated with remarkable recovery results.

7. Policy implications: Indicate any important achieved targets contributing to the future implementation, design or take-up of regional, national or European legislation. Please highlight any potential unintended impacts, bottlenecks or barriers to the implementation of your project due to regional, national or European legislation including recommended actions further to actions already taken to overcome these barriers.

A description of policy implications was discussed in the point 7 of section 6.3. Evaluation of Project Implementation of the present report and a detailed description can be found in *deliverable C.1.6*

7. Key Project-level Indicators

Assess the project's progress towards achieving the Key Project-level Indicator (KPI) targets. If this report is the first report prepared during the project implementation, please ensure that you have finalised the inclusion of data into the KPI database webtool https://webgate.ec.europa.eu/eproposalWeb/kpi/module.
In the case of the Mid-term report, justify any anticipated significant deviations from the targets set initially, and comment on targets already met or exceeded.
In the case of the Final report, please enter the final actual values of the KPIs for your project in the online KPI database (https://webgate.ec.europa.eu/eproposalWeb/kpi) making sure that values reported are justified and consistent with the environmental, economic and social benefits reported in the preceding section. In this section, please provide an analytical comparison with the targets at the beginning of the project.

The update of the LIFE KPI WEBtool it has been made in October 2022. More detailed description in *deliverable C.1.2. or in the WEB*

The methodology elaborated define the indicators and monitoring specifications for the lifetime of the project, that will start at the beginning of the operation phase. The values provided have been collected during the operation and maintenance phase.

A total of 12 indicators have been selected, being the more relevant ones for this project reduction of dangerous substances / waste management and reduction in resource consumption. These indicators are selected taking into account that the non-metallic fraction of PCB is recycled, recovering very valuable metals from this waste stream, reducing the quantity of dangerous substances compared with other traditional treatments. The methane production in the process have been discarded, due to the results obtained in the bench scale with this material, and for this reason, some indicators that were proposed in previous stages of the project have been omitted at this point.

After the project, the treatment capacity is expected to increase gradually, in order to strengthen the procedures and gain enough knowledge about this innovative technology. All the knowledge gained in this project was essential to adequately design and estimate the needs for a potential industrial scale. The results obtained in the economic, environmental and technical viability have been used to estimate the indicators.

Main indicators:

Indicator 3.1. Waste management

In this KPI the reduction of non-appropriately managed waste is quantified, therefore, the trend in this KPI should be negative:

Reduction of unused PCB of WEEE	[ES/ES2/ES21/ES211]	16 02 16 components removed from discarded equipment other than those mentioned in 16 02 15	j. Amount collected by project	0	27.51	900	tn/year
Reduction of unused PCB of WEEE	[ES/ES2/ES21/ES211]	16 02 16 components removed from discarded equipment other than those mentioned in 16 02 15	i. Mass reduction due to appropriate disposal	0	0	0	tn/year
Reduction of unused PCB of WEEE	[ES/ES2/ES21/ES211]	16 02 16 components removed from discarded equipment other than those mentioned in 16 02 15	h. Mass reduction due to appropriate storage	0	0	0	tn/year
Reduction of unused PCB of WEEE	[ES/ES2/ES21/ES211]	16 02 16 components removed from discarded equipment other than those mentioned in 16 02 15	g. Mass reduction due to energy recovery	0	0	0	tn/year
Reduction of unused PCB of WEEE	[ES/ES2/ES21/ES211]	16 02 16 components removed from discarded equipment other than those mentioned in 16 02 15	f. Mass reduction due to incineration with no energy recovery	0	0	0	tn/year
Reduction of unused PCB of WEEE	[ES/ES2/ES21/ES211]	16 02 16 components removed from discarded equipment other than those mentioned in 16 02 15	e. Mass reduction due to digestion	0	0	0	tn/year
Reduction of unused PCB of WEEE	[ES/ES2/ES21/ES211]	16 02 16 components removed from discarded equipment other than those mentioned in 16 02 15	d. Mass reduction due to composting	0	0	0	tn/year
Reduction of unused PCB of WEEE	[ES/ES2/ES21/ES211]	16 02 16 components removed from discarded equipment other than those mentioned in 16 02 15	c. Mass reduction due to recycling	0	27.51	900	tn/year
Reduction of unused PCB of WEEE	[ES/ES2/ES21/ES211]	16 02 16 components removed from discarded equipment other than those mentioned in 16 02 15	b. Mass reduction due to preparation for reuse	0	0	0	tn/year
Reduction of unused PCB of WEEE	[ES/ES2/ES21/ES211]	16 02 16 components removed from discarded equipment other than those mentioned in 16 02 15	a. Mass reduction due to waste prevention	0	0	0	tn/year
Reduction of unused PCB of WEEE	[ES/ES2/ES21/ES211]	16 02 16 components removed from discarded equipment other than those mentioned in 16 02 15	Mass of non-appropriately managed waste	900	872.49	0	tn/year

Figure 13. Indicator Values - 3.1. Waste management.

Nowadays, PCBs are incinerated in copper refineries because there is not a cost-effective method able to recover the metals. Approximately, REYDESA manages 300 Tn/year of PCBs from WEEEs annually and the 100% of them are sent outside to be treated through pyrometallurgy. This indicator is focused on the availability to increase the in-house management of this waste, with a technologically, economically and environmentally viable process. With this new process, the metallic fraction (which represents 60% of the total amount) is fully recovered in the mechanical treatment, and the resulting non-metallic fraction of PCBs could be recycled with the innovative bioleaching technology. Taking into account the economic viability of the project, the expected quantity of PCBs to be treated beyond 3 years of the project in order to make the process viable will reach 900 tons per year, but only 300 tons are generated in REYDESA, the rest of PCBs will have to be purchased in order to reach that quantity.

For this reason, in this indicator it is taken into account the proper management of the 900 tons/year of PCB beyond years after the project, there is no need to send waste to be managed outside, and the indicator have an expected value of 0 tons of PCB of on-appropriately managed waste.

During the project, 27.51 tons of PCB are treated, reducing the quantity to be sent outside to 872.49 tons.

Indicator 5.1.1 Chemicals released

This indicator is selected because one of the expected results of this new process is the reduction of chemicals needed to extract the metals from the waste. These chemicals have an important economic cost, and an associated environmental impact.

Specific Context	Selected Overarching Context Items	First Level Descriptor	Second Level Descriptor	Begin Value	End Value	Beyond 3 Years Value	Unit
Reduction of unused PCB of WEEE	[ES/ES2/ES21/ES211]	ECHA list of registered substances (include EC number/name in comment box)	Substance in ECHA list of registered substances	4500	4393.3	1008	tn/year released

Figure 14. Indicator values – 5.1.1 Chemicals released.

Nowadays, the conventional methods for the recovery of metals from the non-metallic part of PCB of WEEE have low efficiency and a negative environmental impact, because they are directed to incineration without energy recovery and generating emissions. Other alternative, hydrometallurgy, is based on the use of chemicals, that have also an important economic cost for the reagents, and an associated environmental impact. These values are calculated taking into account the treatment of 900 tons of PCB, at the beginning by hydrometallurgy, at the end of the project, 27.51 tons by Bioleaching, increasing this quantity to 900 tons 3 years after the project end.