fenix

WP2 – NEW BUSINESS MODELS & PILOT PLANTS SUSTAINABILITY ASSESSMENT

Task 2.2 PILOT PLANTS SUSTAINABILITY ANALYSIS

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Deliverable No.:	2.2 – Version 008
Work Package No.:	WP2
Date:	30-10-2020
Project No.:	760792
Classification:	Confidential
File name:	FENIX D-2-2 Pilot Plants Sustainability Analysis - Final.pdf
Number of pages:	39

Status of deliverable

Action	By	Date (dd.mm.yyyy)
Submitted (author(s))	Reinhard Ahlers	31-10-2020
Responsible (WP Leader)	Reinhard Ahlers	31-10-2020
Approved by Peer reviewer		

Revision History

Date (dd.mm.yyyy)	Revision version	Author	Comments
29.10.2020	Version 06	Reinhard Ahlers	
30.10.2020	Version 06	Ionela Birloaga	
30.10.2020	Version 06	Cristian Aionesei	
31.10.2020	Final Version	Reinhard Ahlers	

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ABSTRACT

The focus of workpackage 2 is the evaluation of the FENIX project implementations. This deliverable covers the sustainability assessment of the different pilot plants developed and tested within the FENIX project. Deliverable 2.2 focuses mainly on the financial and environmental aspects. A further deliverable will focus on the social assessment of the FENIX results and will be delivered at the end of the project.

In the FENIX project three main supply chains have been developed and implemented. Every supply chain ended up in a separate use case. All three chains started with the disassembly processes of mobile phones and followed by the recycling process. While the recycling process delivers the gold material, extracted from the e-waste directly to the jewellery production, the other extracted materials (mainly copper) are delivered to an up-scaling process. Within this process the copper is prepared to produce ink and advanced filaments for additive manufacturing.

The economic and ecological assessment of the process chains has been performed based on actual data measured, collected, and delivered by the different process owners. Deliverable 2.2 documents the current results of the implementations which are under continuous improvement.

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Abbreviations and Acronyms:	
AFP	Aerosol formation potential
AP	Acidification Potential
AM	Additive Manufacturing
BAL.LCPA	BALance Life Cycle Performance Analysis
BM	Business Model
BoM	Bill of Material
CAPEX	Capital Expenditure
CBM	Circular Business Model
CED	Cumulative Energy Demand
EP	Eutrophication Potential
e-waste	Electronic waste
GWP	Greenhouse warming Potential
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Costs
LCI	Life Cycle Inventory
NVP	Net-Present Value
OPEX	Operational Expenditure
Prm	Percentage of recycled materials
WEEE	Waste of Electrical and Electronic Equipment

1. INTRODUCTION

The ecological awareness of customers is increasing in Europe. Therefore, the efficient recovery of secondary resources must be assured. The FENIX project has started to improve the recycling processes and to make better use of electronic waste in the future. This requires better recycling processes but also the optimization of the process chain starting from disassembly up to the production of recycled products.

To reach this goal FENIX has defined and tested different approaches for disassembly, recycling, and up-scaling of recycled material. These processes are interconnected and form three supply chains with the aim of creating three different products (jewelry, filament for additive manufacturing and ink for additive manufacturing). All three supply chains started with the disassembly processes of mobile phones and followed by the recycling process. While the recycling process delivers the gold material, extracted from the e-waste directly to the jewellery production, the other extracted materials (mainly copper) are delivered to an up-scaling process. Within this process the copper is prepared to produce ink and advanced filaments for additive manufacturing.

To evaluate the processes developed by the project and to verify the economic viability as well as the ecological impact an LCPA (Life Cycle Performance Assessment) has been performed. LCPA covers the LCC (Life Cycle Cost) evaluation and the LCA (Life Cycle Assessment). During the project different assessment models have been developed to compare the different approaches by using the BAL.LCPA software tool. The tool allows the quick adaptation of the models due to pilot implementation changes and the definition of additional assessment parameters. The different assessment results are visualised and stored in the database for further use.

The challenge of the assessment is to analyse each process individually to identify improvement potentials but also to optimize the entire supply chain. This deliverable describes the most important results and parameters of the assessments.

2. OBJECTIVE OF THE BUSINESS MODELS SUSTAINABILITY ANALYSIS

There are a variety of definitions for sustainable business models available. But for sure the future of companies, the environment, and society depends on the consideration of sustainability aspects. David & Martin [1] claim a corporate management strategy to create new modes of differentiation, embedding societal value into products and services, reshaping business models for sustainability and define new measures of performance.

FENIX contributes to this important approach. The treatment of e-waste will get more important in the future assuming that the goals of sustainability are the preservation of natural resources. Business models have been developed in FENIX to achieve these goals. These business models are based on:

- cooperation in recycling and production beyond company boundaries,
- defining of optimal logistical processes and the
- use of recycled materials from e.g. electronic items for new products.

In general sustainability refers to four distinct areas (pillars): economic, environmental, social and human as defined by the RMIT University [2].

Economic sustainability: Economic sustainability aims to maintain the capital intact and to improve the standard of living. In the context of business, it refers to the efficient use of assets to maintain company profitability over time. The approach that continuous growth is good even when it harms the ecological and human environment is becoming less important. New economics approches include also natural capital (ecological systems) and social capital (relationships amongst people).

Environmental sustainability: Environmental sustainability aims to improve human welfare through the protection of natural resources (e.g. land, air, water, minerals etc.). The consideration of environmentally sustainability lowers the risk of compromising the needs of future generations. It has to be considered how business can achieve positive economic outcomes without doing any harm, in the short or long-term, to the environment.

Social sustainability: Social sustainability aims to preserve social capital by investing and creating services that constitute the framework of our society. This requires a larger view of the world in relation to communities, cultures and globalisation. Social sustainability focuses on maintaining and improving social qualities like cohesion, reciprocity, social equality, honesty and the importance of relationships amongst people. The idea of sustainable development, as defined by the United Nations sustainable development goals belongs to social sustainability. The assessment of the social sustainability of the FENIX results will be part of a further deliverable.

Human sustainability: Human sustainability is not part of the FENIX assssment, but is mentioned to complete the description of the 4 pillars. It aims to maintain and improve the human capital in society. Investments in the health and education systems, access to services, nutrition, knowledge and skills are examples for human sustainability. In the context of business, an organisation will view itself as a member of society and promote business values that respect human capital. Human sustainability focuses on the importance of anyone directly or indirectly involved in the making products or offering services.

The four pillars of sustainability should be considered to create new products and servcies as far as possible. In some cases the unique characteristics of the pillars may overlap but it is important to identify the specific type of green business to focus on.

3. THE BAL.LCPA TOOL AND THE KEY PERFOMNCE INDICATORS

The Life Cycle Performance Assessment (LCPA) includes the ecological perspective (LCA - Life Cycle Assessment) and the economical perspective (LCC - Life Cycle Costs) for products and processes between the supply chain stakeholders.

The different FENIX processes have been compared to find the optimal ecological and economical solution. Analyses and choices about the end-of-life of the products and the second life of the materials are made based on product data (e.g. the Bill of Material) and the measurement at the FENIX pilot installations.

The LCPA assessment is based on complex mathematical models and is carried out by the commercial available BAL.LCPA (BALance Life Cycle Performance Assessment) tool. The input KPIs have been defined in cooperation with the different process owners (disassembly, recycling and up-cycling). LCPA results are a combination of various KPIs including life cycle costs, Global Warming Potential and the cumulative energy demand.

For the FENIX assessment the following economical paramaters were selected from the set of possible parameters.

KPI	Description
NPV	Net-present value - some future value of the money when it has been invested
External costs	E.g. costs for environmental damages
Payback time	Period required to recoup the money expended in an investment
Amortisation	Spreading the cost of an intangible asset over a specific period of time

Table 1: KPIs for the economical assessment

The following ecological parameter have been selected for the environmental assessment.

KPI	Description
Amount	Amount of materials used in in the recycling process
Input raw material (material to process)	Indicate the materials involved like e.g. metals, minerals, plastics, textile, organic & inorganic intermediate products, paints, etc.
Electricity	Specify the Grid Mix indicating the country, or the specific mix known (e.g. 40% nuclear, 60% hydroelectric)
Water consumption	Indicate water consumption for the production
Generated waste	Define waste typology (e.g. plastic, inert, hazardous, metals, wastewater, liquid, emission)
Destination and means of transport	Define the transport destination and the mean of transport (truck, train, ship etc.)

Table 2: KPIs for the environmental assessment

Not all parameters have been applied to all processes but only where they made sense. This is based on decisions made by the modeler.

4. CHARACTERISTIC OF THE INPUT MATERIAL

Waste of Electrical and Electronic Equipment (WEEE) is a complex mixture of materials and components which can partly be recycled and reused. Another part of the waste contains hazardous materials which can cause major environmental and health problems if not managed in a proper way. WEEE includes e.g. computers, TV-sets, fridges, washing machines, desktop PCs, notebooks and mobile phones. The waste of electrical and electronic equipment is one the fastest growing waste streams in the EU, and it is expected that it will grow to more than 12 million tons by 2020 [Source: https://ec.europa.eu/ environment/waste/weee/index_en.htm].

Two directives entered into force to address this problem. The directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS Directive) requires heavy metals such as lead, mercury, cadmium, and hexavalent chromium and flame retardants to be substituted by safer alternatives.

The second WEEE Directive (Directive 2002/96/EC & Directive 2012/19/EU) provided collection schemes where consumers return their WEEE free of charge. These schemes aim to increase the recycling of WEEE and/or re-use and is therefore interesting for the FENIX project.

Large household appliances accounted for 1.9 million tonnes, corresponding to 51.8 % of the total WEEE collected in the EU in 2017 (see Figure 1). [Source: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics_-_electrical_and_electronic_equipment].

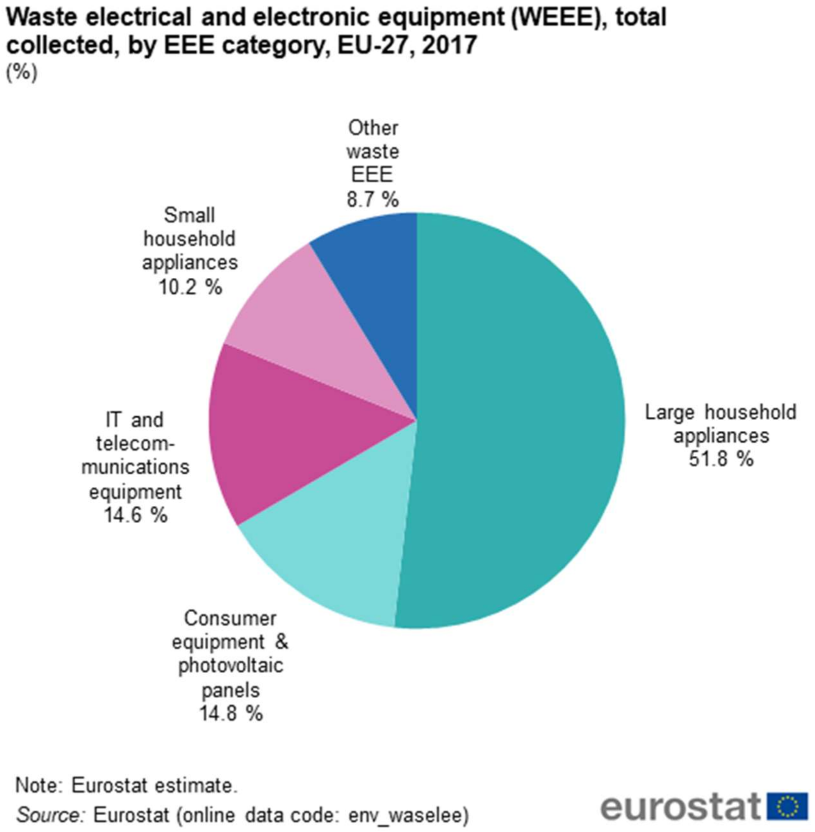


Figure 1: WEEE collected by the main EEE categories in 2017

The EUROSTAT estimation shows that the second and third largest categories for WEEE collection in the EU, accounting for around 555 thousand tonnes was the consumer equipment and photovoltaic panels (14.8 %) followed by IT and telecommunications equipment (14.6 %) with 547 thousand tonnes. The production of modern electronics requires the use of scarce and expensive resources (e.g. around 10% of total gold worldwide is used for electronic equipment production). To improve the environmental management of WEEE and to contribute to a circular economy and enhance resource efficiency the improvement of collection, treatment and recycling of electronics at the end of their life is essential. This shows the importance of the FENIX results. What is tested here with mobile phones can of course also be applied to other kinds of WEEE.

The main challenge of the old mobile phone collection is to get people to return their old products for recycling when they no longer need them. One inhibiting factor for recycling of mobile phones is the willingness to keep a spare product. The most important factors enhancing the recycling behavior are convenience and awareness on where and how to recycle. This can be supported by IT platforms as developed within the FENIX project.

Environmental risks may take place in the cases where e-waste is not handled properly within the recycling and pre-treatment processes. With proper technologies, 100% of the materials in a mobile phone can be recovered and nothing needs to be wasted. For the moment the FENIX project focuses on the valuable materials of the mobile phones (gold, silver, copper, etc.).

Mobile phones are just one product in a high varity of electronic products. Nevertheless it is one of the prodcusts with the most valuable materials inside. The following table shows the average material content in different product catagories. The FENIX processes have shown that it can differer very much from batch to batch. Therefore the values can only be used as guidelines.

Average material content in Prm (Percentage of recycled materials)	Refrigerator	Wasching machine	Air conditioner	Desktop PC	Notebook	Mobile phone	CRT TV	Stereo system	Digital camera
Iron (Fe)	2.1	9.5	2.0	1.3	3.7	1.8	3.4	1.2	3.0
Copper (Cu)	17.0	7.0	7.5	20.0	19.0	33.0	7.2	15.0	27.0
Silver (Ag)	0.0	0.0	0.0	0.1	0.1	0.4	0.0	0.0	0.3
Gold (Au)	0.0	0.0	0.0	0.0	0.1	0.2	0.0	0.0	0.1
Aluminium (Al)	1.6	0.1	0.7	1.8	1.8	1.5	6.2	2.9	2.4
Barium (Ba)	0.0	0.0	0.0	0.2	0.6	1.9	0.2	0.1	1.6
Chromium (Cr)	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	0.3
Lead (Pb)	2.1	0.2	0.6	2.3	1.0	1.3	1.4	1.9	1.7
Antimony (Sb)	0.3	0.0	0.0	0.2	0.1	0.1	0.3	0.0	0.2
Tin (Sn)	8.3	0.9	1.9	1.8	1.6	3.5	1.8	2.2	3.9
Zinc (Zn)	1.7	0.2	0.5	0.3	1.6	0.5	5.3	1.4	0.9

Remark: 0.2% of Au means 200 g of Au in 1 ton of PCBs

Table 3 Characterisation of metals embedded in specific WEEE (Source: [5])

During the assessment it has been shown that the characterisation of metals inside a product has an high impact on the economic efficiency of the examined process,

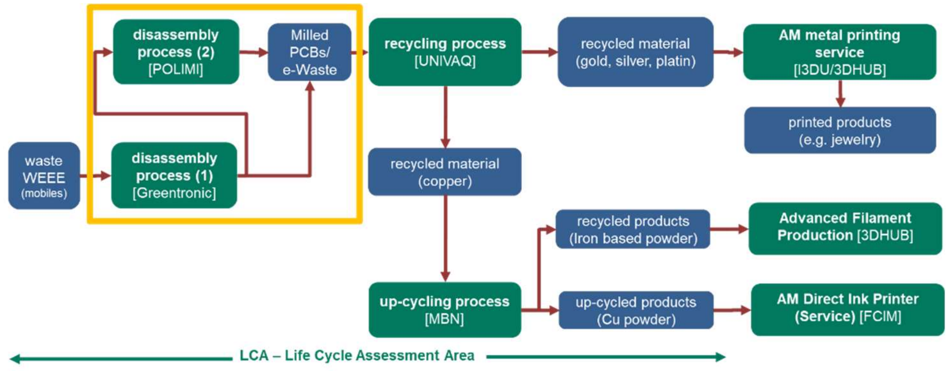
5. OVERALL PROCESS CHAIN ASSESSMENT

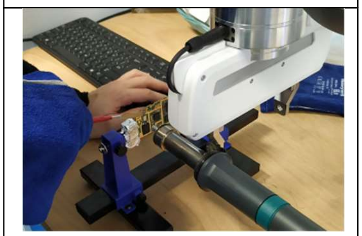
The Life Cycle Cost analysis has been carried out for each process and the interconnections of the processes. The ecological analysis (LCA) has been focused for the whole process chain starting from the disassembly process up to the material recycling/up-scaling process.

The BAL.LCPA (BALance Life Cycle Performance Assessment) tool has been used to carry out the assessment. Measurements at the pilot installation have been used for the assessment as well as market figures were relevant. Because of the amount of assessment parameters only the most relevant parameters are documented within this deliverable.

The assessment starts with the disassembly process. FENIX is not focusing on the e-waste collection process while the improvement potential for green products is very low compared to the conventional processes of today.

5.1. Disassembly process





Process goal:

The focus of the process is to dismantle the mobile phone scrap in an environmentally friendly and cost-effective manner. The dismantled parts should be optimally prepared for the following FENIX recycling processes. The recycling process requires PCBs with rich materials. Batteries and cooling elements do not contribute to the extraction of valuable material. Capacitors even worsen the FENIX recycling processes.

Process description:

Two different disassembly process chains have been tested and evaluated:

(1) Manual process separating housing & batteries
Cobot application to remove capacitors & cooling elements

(2) Manual process separating housing, batteries etc. and shredded

The first chain includes the disassembly process (1) were the housing, display and batterie have been removed by Greentronics and the mobile phone PCBs were shipped to disassembly process (2), were a Cobot removed capacitors & cooling elements [POLIMI].

The second disassembly chain was a pure manual process removing housing, batteries, electronic capacitors, heat sinks, connectors, quartz resonators, inductors, black panels, and multilayer and capacitors. Also RAMs and processors have been extracted from the PCBs. The valuable material has been send directly to the recycling process for the Gold Rec-2 process (see chapter 5.2) and were shredded for the Gold Rec-1 process (see chapter 5.2) before sending it to UNIVAQ.

Identified cost driver:	**Identified environmental challenges:**
(1) Personnel costs (2) Investment costs for cobot (3) Energy consumption and maintenance are minor costs	(1) Energy consumption (2) Transport effort (long distances between FENIX processes)

Assessment model: Fenix Disassembly_v5.lcpa

Key figures within the processes:

Processes / KPIs	**Process 1** Manual process & Cobot application	**Process 2** Manual process separating all items and (shredding)
Investment costs	Cobot Costs: 20.000 €	-
Personal hours per unit	Greentronics: 15 sec. per item Cobot: 245 sec. per item	Greentronics: 45 sec. per item
Personal costs per year	10.000 €/year (process 1) 20.000 €/year (process 2)	10.000 €/year (process 1)
Energy consumption	Very low	0,11 kW
Amount of input material	20 t	
Process results	PCBs only with valuable material and prepared for the hydrometallurgical pilot plant (Gold-Rec 2 process)	PCBs only with valuable material and prepared for the hydrometallurgical pilot plant (Gold-Rec 2 process) and Gold-Rec 1 process if shredded
Destination between disassembly and recycling process	Alexandria (RO) -> Milano (I) 1.700 km	
Means of transport	Truck	

Assessment conditions

The assessment has covered two main points. One was the manual dismantling process supported by a Cobot or as pure manual process.

- The operation time for was 15 sec for the manual process plus 245 sec for the Cobot (optimistic guess – time measurements were much higher) for one mobile phone.
- The operation time for completing the whole disassembly in a manual was about 45 sec.
- The price for the resulting e-waste should not higher than the actual market price of 14 € per kilo.

A second assessment has covered the transport between the location of the disassembly process and the recycling process. While the hydrometallurgical pilot plant for the e-waste recycling is installed in a container it can be transported and operated at different sites (provided the system receives a license to operate). The developed recycling technology allows the transport of the plant to the e-waste instead of its transporting always to the recycling unit.

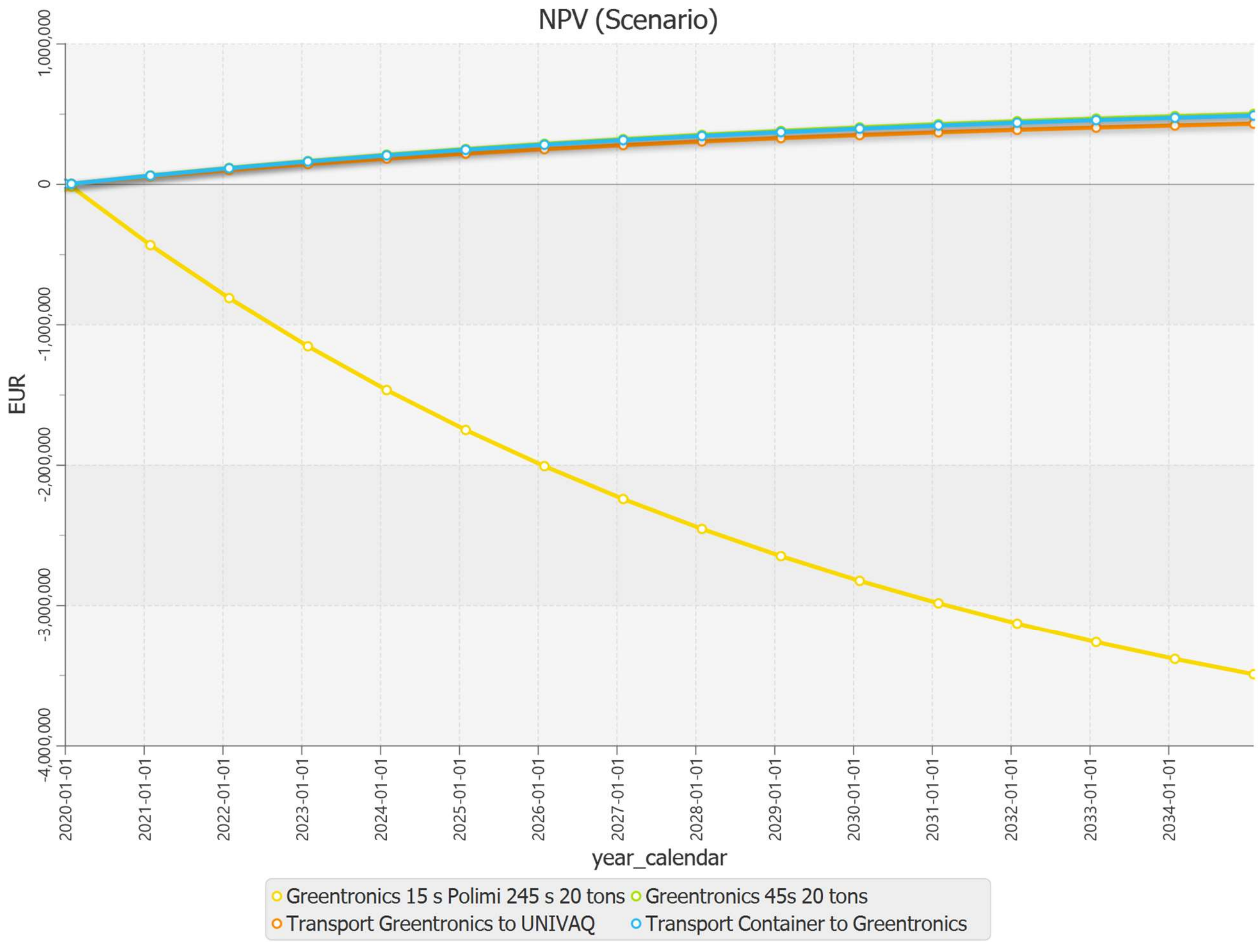


Figure 2: NPV of the disassembly process

Key findings for the disassembly process:

- Poor manual disassembly process is beneficial after a short time (months). The duration depends mainly on the salary rate of the personal.
- Disassembly processes based on a combination of manual and Cobot operations are too expensive and become never beneficial. The reason is the high process time per mobile phone for the Cobot and the investment cost into the hardware.
- Transportation costs have been calculated based on the manual disassembly process. The influence on the NPV is very low over the evaluated period (15 years) that it can be neglected.
- Transportation has an important influence on the GWP (Green Warming Potential) as part of the LCA analysis. Therefore, it has been calculated and the results are demonstrated in the following two figures.

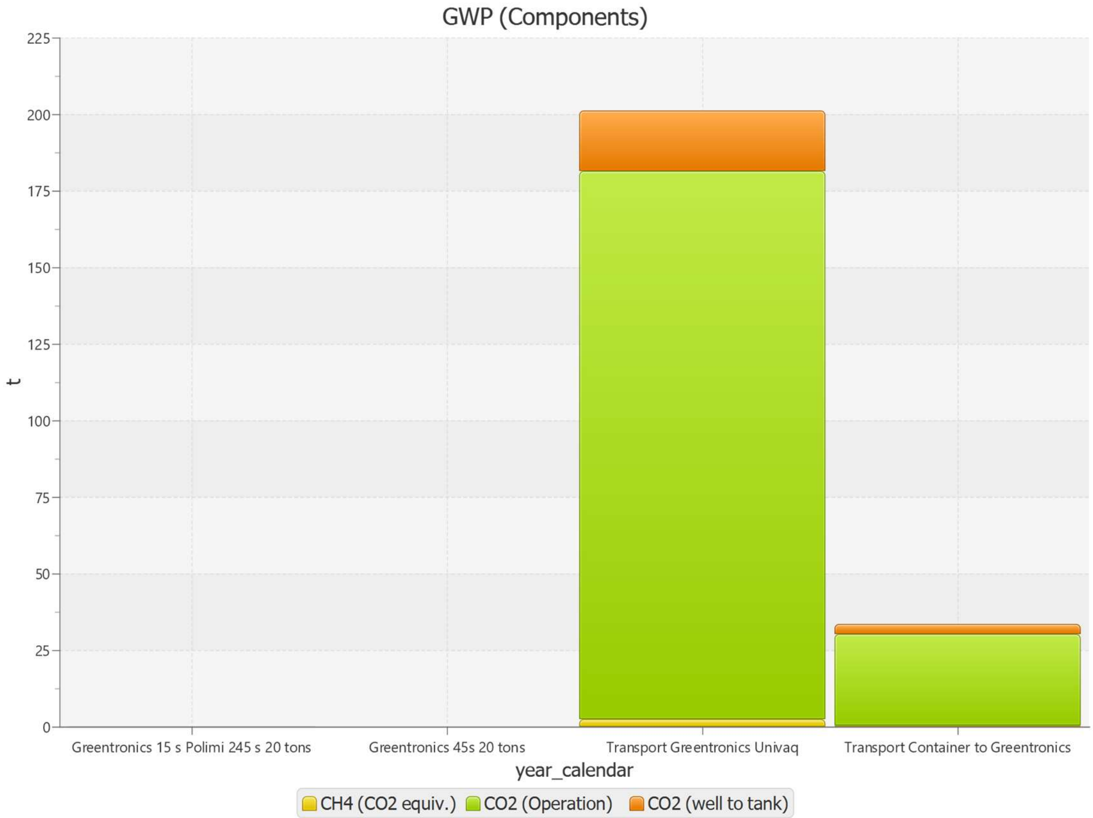


Figure 3: GWP for the PCB transport after disassembly

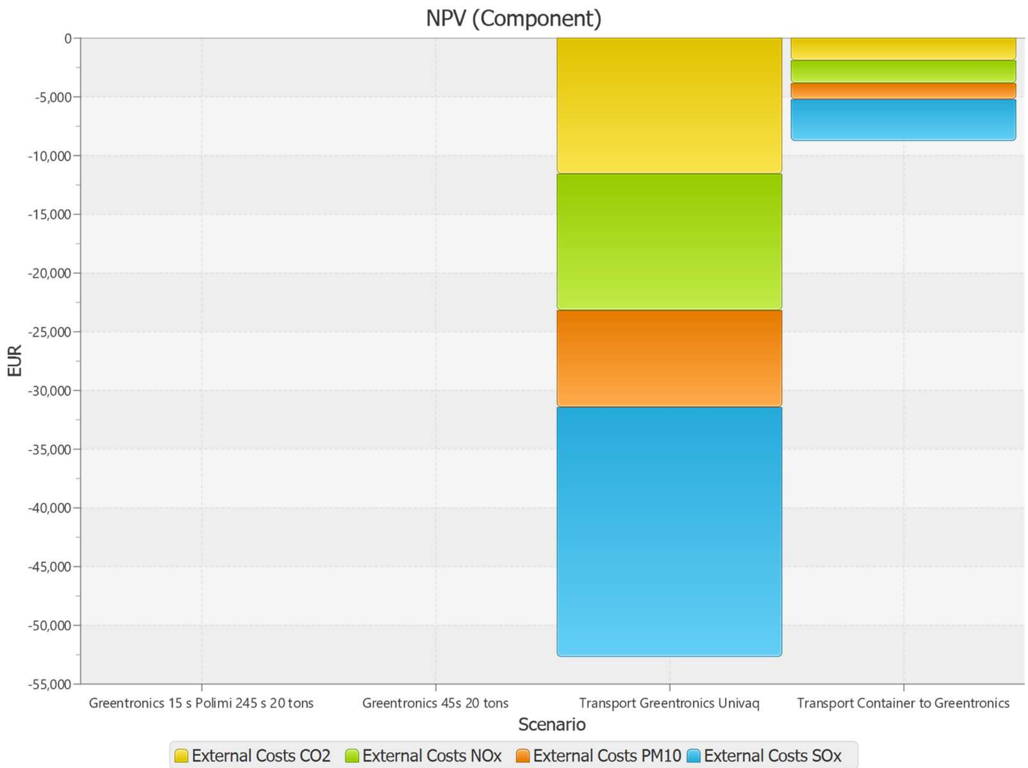
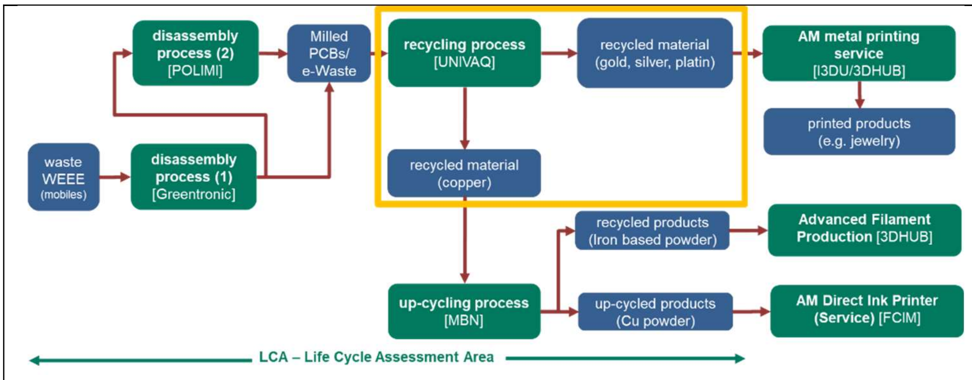


Figure 4: External costs for the PCB transport after disassembly

Key findings for the disassembly process:

- The GWP calculation bases on monthly transport of e-waste to the hydrometallurgical pilot plant. The distance between the two processes is about 1.700 Km and during the transport more than 200 t GWP are produced during the 15 years. The alternative is the transport of the plant to the e-waste once a year and operated the system at the location of the collector.
- There is no noticeable cost difference for the operators of the processes, but the assessment shows a big difference in the external costs. These are costs that are paid by the society (e.g. health consequences of pollution)
- External costs will only become important if the saving of CO_2 is are rewarded and will affect profitability of business processes.

5.2. Recycling process



Process goal:

The main goal is to remove as much valuable material as possible from the waste which was prepared by the disassembly process. The recycling process should be environmentally friendly and cost effective. The result of the recycling processes are the raw materials (gold, silver, copper) as basis for the next FENIX process steps.

Process description:

Two methods of extracting the valuable raw materials from the waste have been tested.

(1) Method 1: GOLD REC-1 to extract a higher amount of valuable material
(2) Method 2: GOLD REC-2 to extract a lower amount of valuable material with less effort

A hydrometallurgical pilot plant has been designed, developed and built to test the different recycling methods. The GOLD REC-2 process enabled an easier handling and is therefore mostly basis for the assessment.

Identified cost driver:	**Identified environmental challenges:**
(1) Personal effort (considereing double shifts) (2) Chemicals up to 39% of the operational costs (3) Operational costs including energy and maintenance	(1) Energy consumption (2) Different chemical left overs which have to be disposed

Assessment model: Fenix UNIVAQ.lcpa

H2020 Innovation Action - This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N. 760792

Steps of the recycling process for Gold Rec-1

(relevant for the LCA)

Step	Input material	Main Process	Sub-Process	Process result	Weight/ Amount	Energy consumption	Water con-sumption	Additive Chemical consumption (Amount and kind of chemicals)
1	Milled WPCBs – mother-boards				15 g			
2		Base metal leaching	-	Sn & Cu solution	104 g	$27.11*10^{-6}$ kWh/batch	100 g (70 for solution preparation and 30 for solid washing)	H_2SO_4 (98% wt./vol.) – 18 g; H_2O_2 (30% wt./vol.) – 22.2 g
				Solid residue	10.3 g			
3	Sn & Cu solution		Sn pre-cipitation	H_2Sn0	1.2 g (with a Sn content of 50%)	$10.2*10^{-6}$ kWh/batch	20 g for tin precipitate washing	Polyamine solution (10% wt./vol.)
4	Cu solution		Cu electro-winning	Cu	3.34 g (with a purity of 98%)	$7.88*10^{-4}$ kWh/batch	20 g	no
				Waste solution and wash water – to recycling	97 g			
5	Au & Ag solution	Au & Ag leaching		Leaching solution	98 g	$10.3*10^{-6}$ kWh/batch	129.45 g (99.45 for solution and 30 for solid residue washing)	CSN_2H_4 (99% of purity) – 2 g; $Fe_2(SO_4)_3$ (99% of purity) – 2.18 g; H_2SO_4 – 0.99 g
				Solid residue (with 3 ppm of Au - to disposal)	10.2 g			
				Wash water of residue to recycling	30 g			
6	Au & Ag solution	Au electro-winning		Au and partial Ag	1.3 mg of Au and 1.25 of Ag	$1.5*10^{-5}$ kWh/batch		no
7	Ag solution	Ag electro-winning		Ag	1.3 mg	$1.9*10^{-5}$ kWh/batch		no
				Waste solution– to recycling	68.6 g			
				Wastewater	29.4			
8	Waste-water	Wastewater treatment		Solid residue – to disposal	4.11 g			
				Treated solution – to recycling at precious metals leaching step	31.6 g	$10.3*10^{-6}$ kWh/batch		H_2O_2 (30% wt./vol.)- 2.775 g; $FeSO_4*7H_2O$ – 1 g; CaO (10% wt./vol.) – 16.23

Assessment conditions

The Gold Rec-1 process requires shredded PCBs. Which requires an additional investment and additional process step within the recycling process. The recycling plant developed and installed in the FENIX project is suitable for semi-automated operation (Invest 250.000 €) which requires a high proportion of manual intervention during the processes.

Key findings for the Gold Rec-1 recycling process:

The assessment of Gold Rec-1 has shown that the recycling plant needs an additional investment to be able to carry out fully automated processes.

In summary it can be stated that a beneficial operation of the plant under **Gold Rec-1 conditions** is only possible with triple shift and automated operation.

Steps of the recycling process for Gold Rec-2

(relevant for the LCA)

Step	Input material	Main Process	Process result	Weight/ Amount	Energy consumption	Water consumption	Additive Chemical consumption (Amount and kind of chemicals)
1	Waste Materials	-	-	38.5 g			
2		Leaching	Solid Residue	35.3 g - 12 ppm Au and 12.3 % of Cu [to be crushed for further glass fibre and residual Cu recovery]	20.11 $*10^{-6}$ kWh/batch	131.66 g (81.66 for solution and 50 for washing of solid residue)	HCl (37% wt./vol) - 69.41 g; $C_2H_4O_2$ (99% wt./vol.) – 21 g; H_2O_2 (30% wt./vol.) - 44.4 g
			Au & Ag & Cu solution	216 g			
3	Au & Ag & Cu solution	Au Reduction	Au Metal	26.28 mg of gold in a precipitate of 31 mg (purity of 84.4%)	7.3*10^{-6} kWh/batch	20 g (for washing of precipitate)	$C_6H_8O_6$ (99% of purity) – 1 g
			Wash water [to reuse into the leaching process]	20 g	-	-	-
4	Ag & Cu solution	Ag Precipitation	AgCl and Cu precipitate	2.4 g of Cu in a precipitate of 2.87 (purity of 83.46 %)	23.11*10-6 kWh/batch	30 g (for washing of precipitate)	Fe metal powder – 5 g
			$FeCl_2$ Solution	215 g To be considered for selling industrial waste water treatment plants			
5	Wash water of Cu precipitate	AgCl recovery	AgCl	10.69 mg in a precipitate of 25 mg (42 % of purity)	3.11*10-6 kWh/batch	20 g	Polyamine solution of 10 % wt./vol - 0.5 ml
			Wash waters [to reuse into the leaching process]	40 g			

Assessment conditions

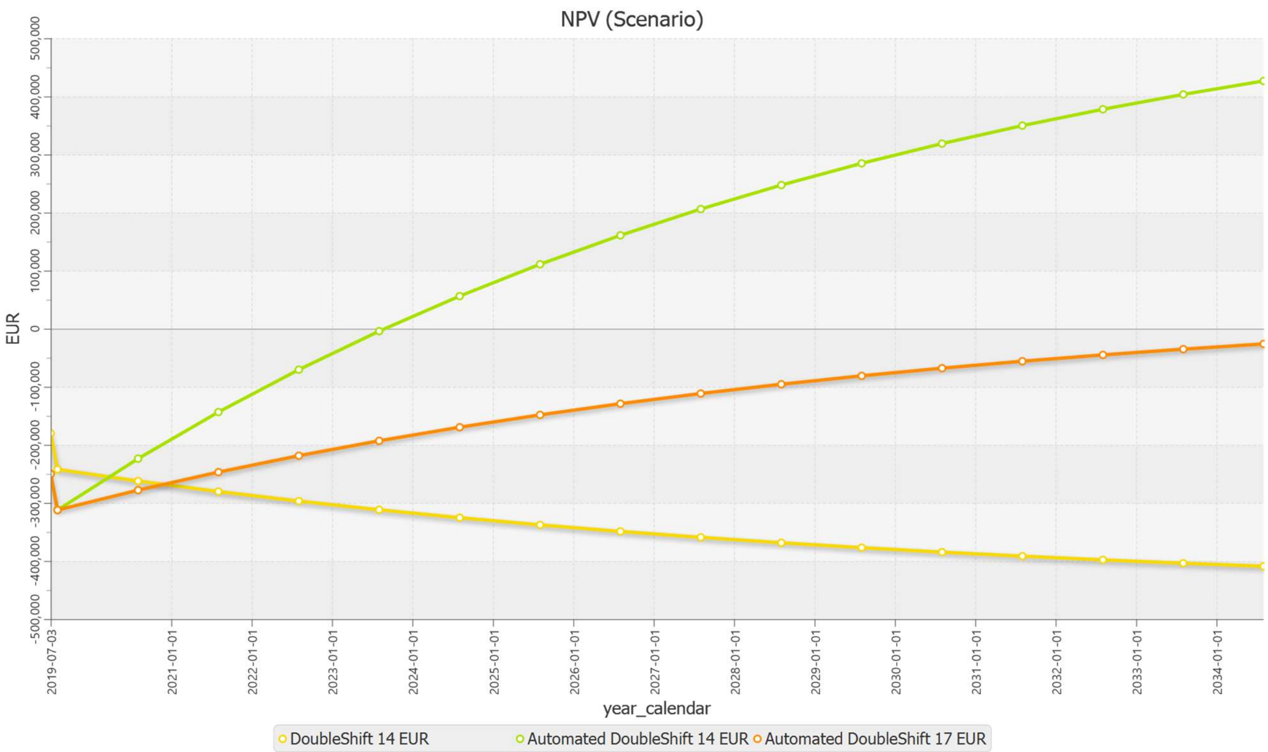
Assessment results depend very much on the

- richness of the waste material,
- Purchasing prices for PCBs (about 60% – 67% of material value)
- Raw material market prices
- Operational costs

Investment costs of the pilot plant (automated): 434.000 €

Double shift with automation (1 operator per shift to feed the process with material and to control the process)

Expected process volume: 20 t/year



Key findings for the GOLD Rec 2 recycling process:

- The semi-automated material recovery plant operated in two shifts will not become beneficial (yellow curve)
- The **automated material recovery** plant will become beneficial after 5 years with a PCB purchasing prices of 14 €/kg (price of the incoming e-waste).
- The **automated material recovery** plant will become beneficial after 14 years (PCB purchasing prices of 15,5 €/kg. This shows the hight impact of the raw material price for this process.
- Richer materials and more efficient processes would shorten the time significantly

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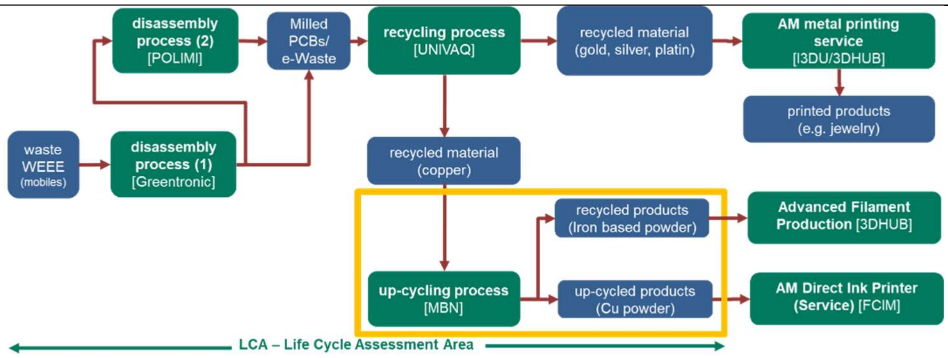
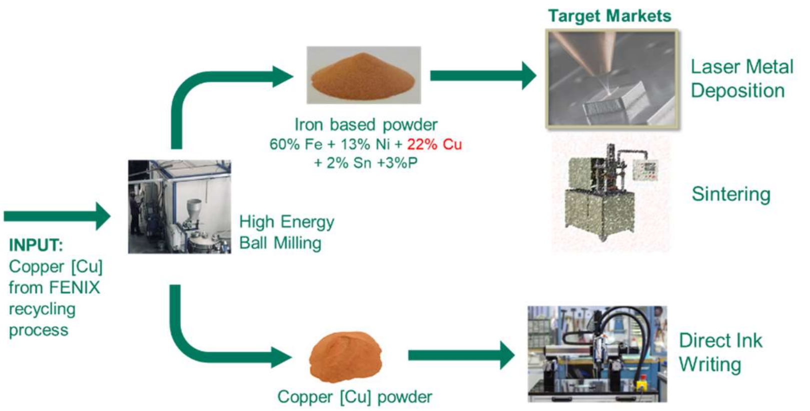
5.3. Upcycling process





Process goal:

Refinement of the copper generated by the FENIX recycling processes to prepare metal powder for the ink production (use case 1: Direct Ink Writers) and the production of advanced metal-based filaments (use case 3). Additionally, the metal powder should be directly sold to the market for e.g. laser metal deposition and sintering.

Process description:

High energy ball milling is the central process to produce copper-based powder (pure or mixed) for different applications.

The recycled powder is processed with fresh raw element powders, (i.e. Fe, Ni, P) to produce an alloy suitable for sintering processes, the ratio between pristine and recycled materials is adjusted batch by batch according with the composition of the recycled powder. In the High energy ball milling step process the different powder are alloyed at solid state and RT conditions, thanks to the energy released in each impact by the milling means with the powder. Once the alloyed powder is obtained it is post-processed to enhance the morphology and particle size distribution.

A tumbling mill is used to increase the weight % of particles in the usable size range (i.e. particles smaller than 60μm) and sieves are used to tailor the size distribution (i.e. bimodal or monomodal). Laser diffraction analysis assess the final size distribution of the batch of powder, that is than used to compound a feedstock for robocasting.

Identified cost driver: (1) Personal effort (2) Energy costs (3) Investment costs	**Identified environmental challenges:** (1) Energy consumption
Assessment model: Fenix_MBM v2.lcpa	

Steps of the upscaling process:

Step	Input material	Main Process	Process result	Secondary processes	Process result	Weight/ Amount	Energy consumption	Personnel effort per kg	Process time per kg
1	Raw elements [Copper from recycling process]	-			-	1,0 kg			
2		High Energy Ball Milling	Copper powder / Iron based powder (60% Fe – 13 % Ni -22% Cu – 2% Sn – 3%P)	Sieving	Copper powder / Iron based powder (60% Fe – 13 % Ni -22% Cu – 2% Sn – 3%P)	0,40 kg	10,33 KWh [per kg]	1,67 hours	3,58 hours
					Coarse Powder [reusable] in ball milling	0,60 kg			

The process time is biased by the fact that FENIX is using smaller batch sizes. By scaling up the capacity with current available technologies personnel effort per kg would drop to 0,4 hours/kg. There is equipment available that could process even bigger quantities, corresponding to less than 5 min per kg.

Assessment Conditions

All figures are average values based on market information and measurements at the pilot installation. The NPV assessment focuses on different utilization degrees of the high energy ball milling machine. The basic figures of the investment are:

- Investment for the high energy ball milling machine: 15.000 €
- Maximal powder output of 447 kg/year is based on the machine used in the project. By current processing amounts, powder processing can be scaled up to 7 ton/year quite easily (on the smaller or our industrial plants)
- Operation time of the High Energy Ball Milling Machine: 1.600 h/year
- Personal effort of 746 h/year (person hours per year = 1.400 h) for maximal powder output of 447 kg/year is the basis for the assessment.
- This requires a continuous personal effort of roughly 0,53 person months

For the iron-based powder, the following additional material is needed:

Kind of required input material	Amount of material based on the final product in percentage [full utilization]	Market price considered in the assessment	Yearly cost for full machine utilization
Copper [Cu]	22% [98 kg]	8 €/kg [min:1,48 - max:24,43]	784,00 € From FENIX recycling
Iron [Fe]	60 % [268,2 kg]	2 €/kg [min:1,25 - max:8,55]	536,40 €
Nickel [Ni]	13 % [58,11 kg]	25 €/kg [min:19,8 - max:35]	1.452,75 €
Tin [SN]	2 % [8,94 kg]	23 €/kg [min:22 - max:25]	205,62 €
Phosphorus [P]	3% - [13,41 kg]	21 €/kg	281,61 €

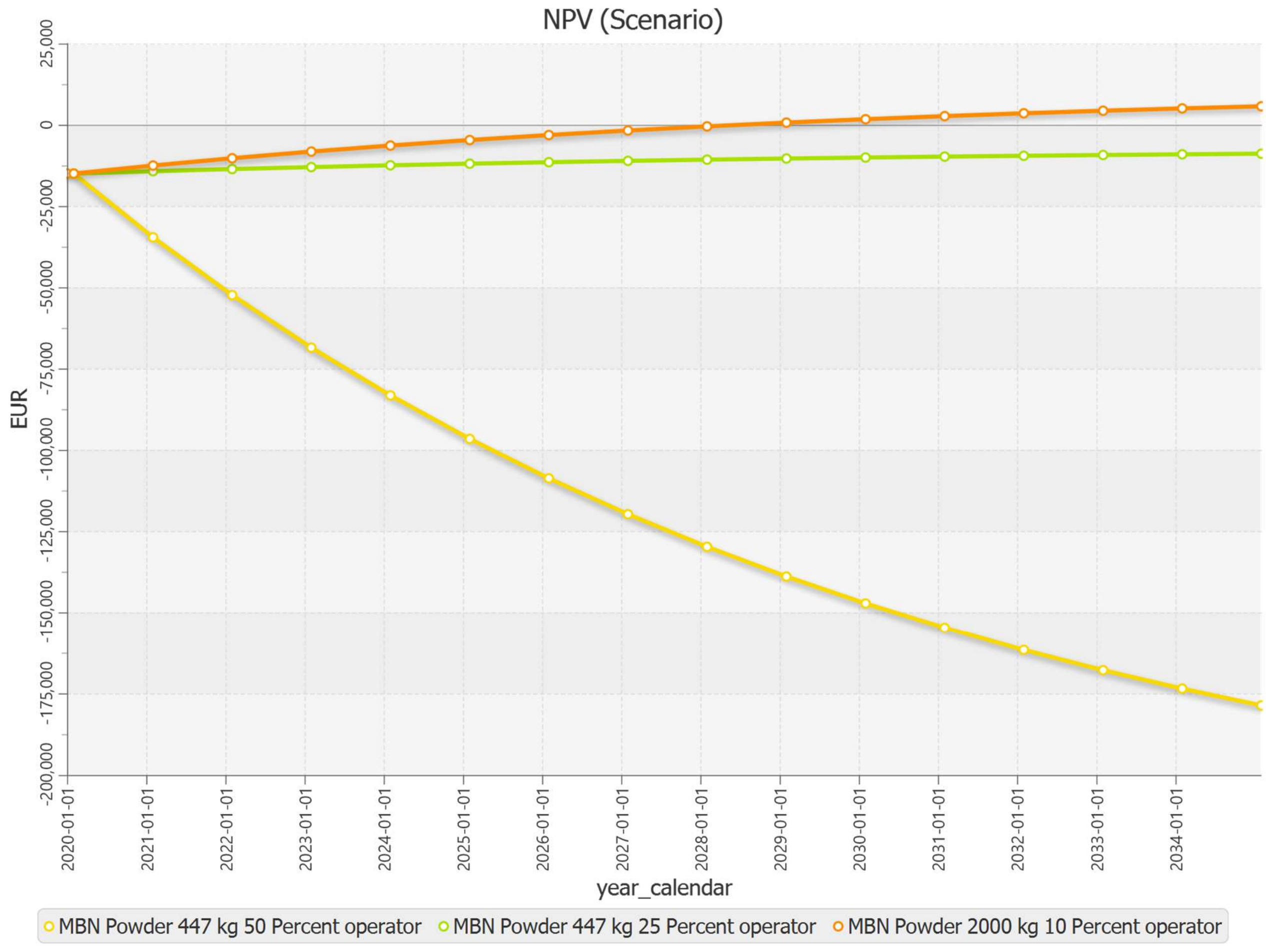
Market prices for the recycled powder products:

MBN does not commercialize pure copper powders. Nevertheless, different Copper-based products are available ranging from 40 to 60 €/kg (price affected by Copper content and application). FENIX Cu-Based version can target the highest price range, regardless the high oxygen content that normally should be enough to put it in the low-grade category.

The current version of Iron-based powder is sold at 30 to 40 €/kg, according with the amount and grade. The FENIX version can stay on the same price range. Specific market condition might make possible to increase the price up to 70-80 €/kg, such as in additive manufacturing.

Revenue assessment bases on 60 €/Kg * 447 kg = 26.820 € for mixed powder

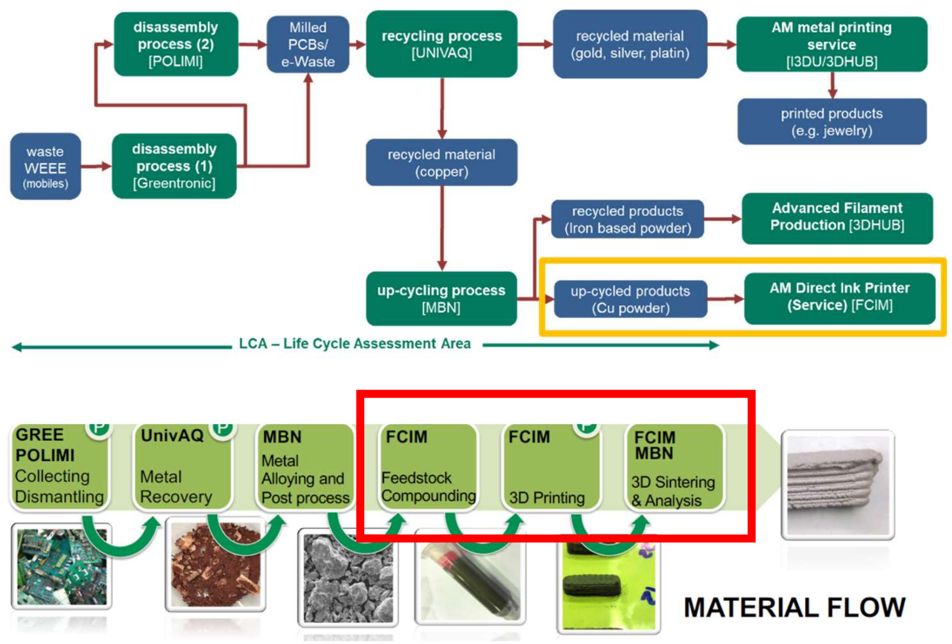
Revenue assessment bases on 50 €/kg * 447 kg = 22.350 € for Cu powder

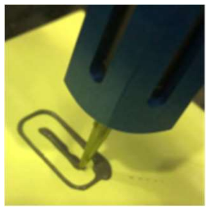


Key findings for the up-cycling process:

- Official market price for copper and additional materials was used for the assessment.
- Production is running on a laboratory level (small amount [447 kg per year] with high personal effort) will not become beneficial
- A material output of 2 t per year and a much lower personnal effort (industrial production) will assure a payback time after 8,5 years.
- Profitability of the production process depends very much on output quantities.

5.4. Recycling Use Case 1: Metal powder and Robocasting





Detail design of the new equipment

Process goal:

The use case 1 “Metal powder and Robocasting” is dived into two activities. The first activity is the production of ink for DIW (Direct Ink Writing) printers from the materials of the FENIX upscaling process. Within this activity the FENIX ink will be optimised to enable lower sintering temperatures for the printed products. This means that smaller sintering furnaces with lower energy requirements can be used.

Secondly a DIW (Direct Ink Writing) printer is developed for high precise printings. The new DIW works with a pressure of 198 bars (state of the art DIW work with 6 bars) and can produce a higher surface quality and a more precise printing.

The combination of a high-quality printer and ink made from recycled material encounters a gap in the market that will generate greater demand in the future. Because it is ecological and economical optimised and it promises a higher margin.

Process description:

The inck production bases on the copper powder from the FENIX upscaling process. The feedstock compounding has to be combined with a binder (pluronic acid) to generate the paste (ink).

The DIW concept has been defined and realised in parallel. The DIW has been tested by using the FENIX ink. The printed examples have been sintered and finally analysed to optimise the ink and the DIW system.

Identified cost driver:	**Identified environmental challenges:**
(1) Personal effort (2) Investment cost (sintering furnaces)	(1) Energy consumption

Assessment model: Fenix_Robocasting UC-1.lcpa

Development and production of the Direct Ink Writing printers

The DIW has been developed to release a good printing quality for a low printer price (25.000 €). But the new printer should also pave the way to a high selling rate for copper-based ink especially for this printer.

Kind of required input material	Value
Final target market volume per year	3 printers
Material value pro printer	8.300 €
Personal effort (for three printers per year)	0,5 persons
Target market price per printer	25.000 €

The new printer focuses on the 3D printer market of Industrial 3D printer price range: €20,000 – 100,000 € [see: https://3dinsider.com/].

Steps of the DIW ink production process

Step	Input material	Main Process	Process result	Weight/ Amount	Energy consumption	Water consumption	Additive Chemical consumption
1	Iron based powder	-	-	10 cubic centimetres			
2		Feedstock compounding	Metal powder & binder	55 g	-	-	Pluronic acid
3	Metal powder	3-D printing	Printed products	770 g	1,47 kWh/kg	0,1l/kg	Pluronic acid & Dolapix PC75
4	Printed products	Sintering	Final printed products	347 g	4,42 kWh/kg	0	0

Market price for copper filament – 200 cm³ role 358,44 € (Source: https://www.mark3d.com/de/produkt/markforged-kupfer-filament-200-cm%C2%B3-rolle/)

The ink has been specially developed for the new Direct Ink Printer. Therefore, the ink sales are closely coupled with the sales of the DIWs. This dependency is a risk on one site but has the advantage that good prices for the ink can be realised. The assessment models of use case 1 combine the ink and the printer sales processes.

Three different models have been evaluated which includes a conservative scenario (selling one printer per year and increase the number by 1 every year), the progressive scenario (selling three printers per year and increase the number by 3 every year) and finally selling printers and ink based on the conservative scenario.

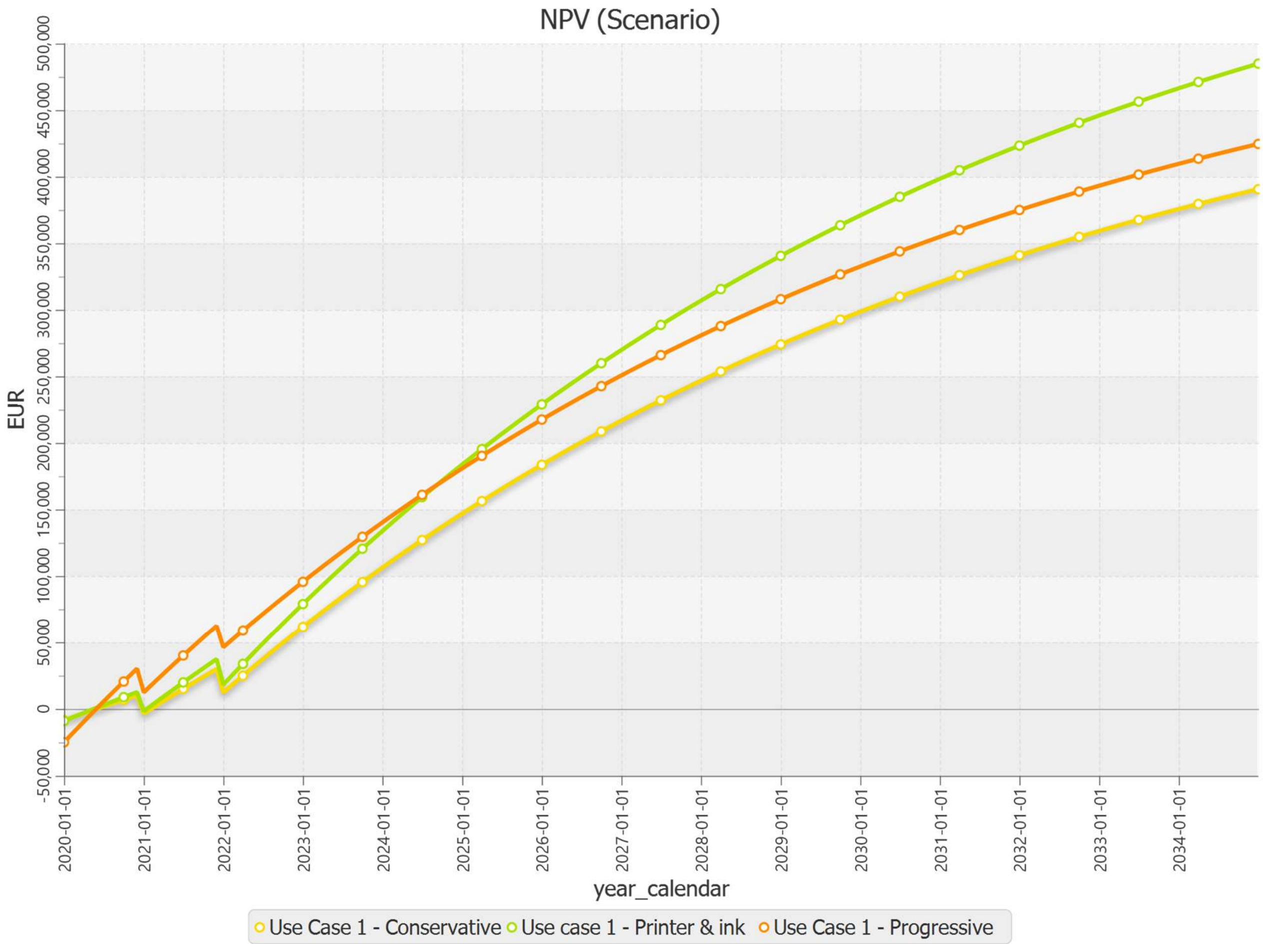
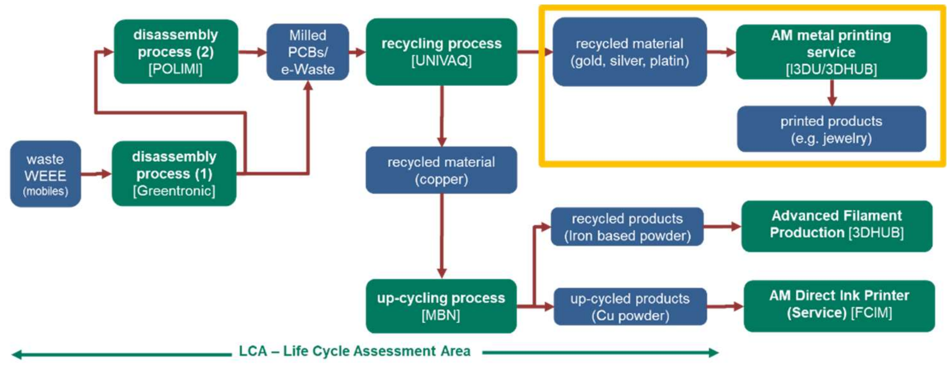


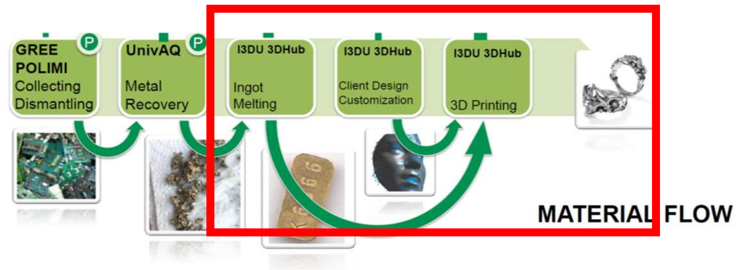
Figure 5: NPV for use case 1 – printer and ink production

Key findings for the ink and DIW printer production:

- NPV focuses on the sale of the printers and the associated special ink generated from recycled material.
- Printer and ink will become beneficial after one year.
- By the combination of ink and printer the income is much higher for recycled material

5.5. Recycling Use Case 2: Jewellery production



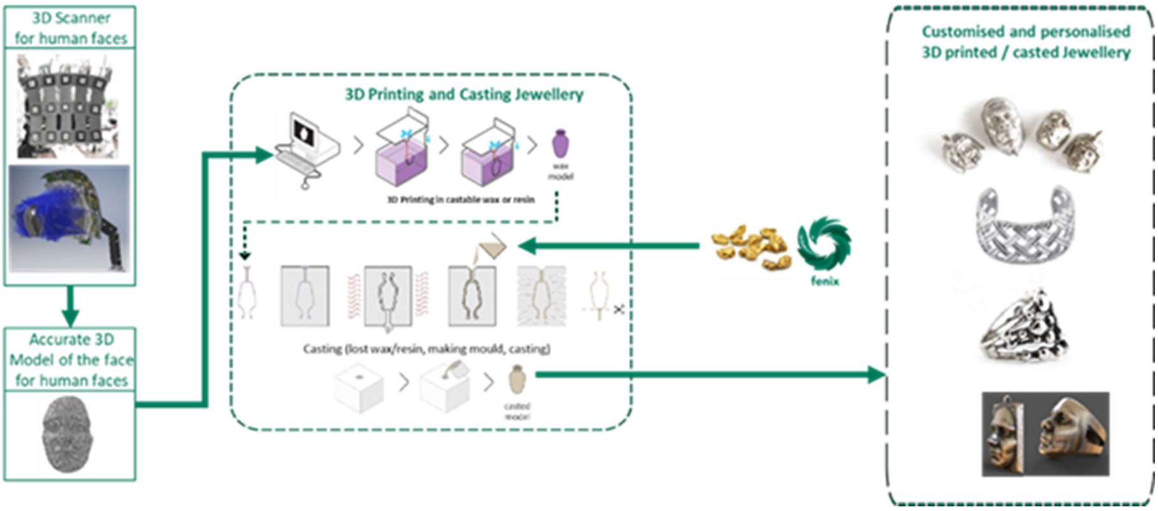


Process goal:

Use case 2 has been started to use the valuable materials of the FENIX recycling process (gold, silver, etc.) to produce personalised jewelleries. the goal is to create sustainable products through personalization and the use of recycled materials, which can generate a higher margin. The use case is separated into the development and production of face scanners for the personalization and the production of jewelleries. The scanners will be placed in jewellery stores which use the FENIX printing service.

Process description:

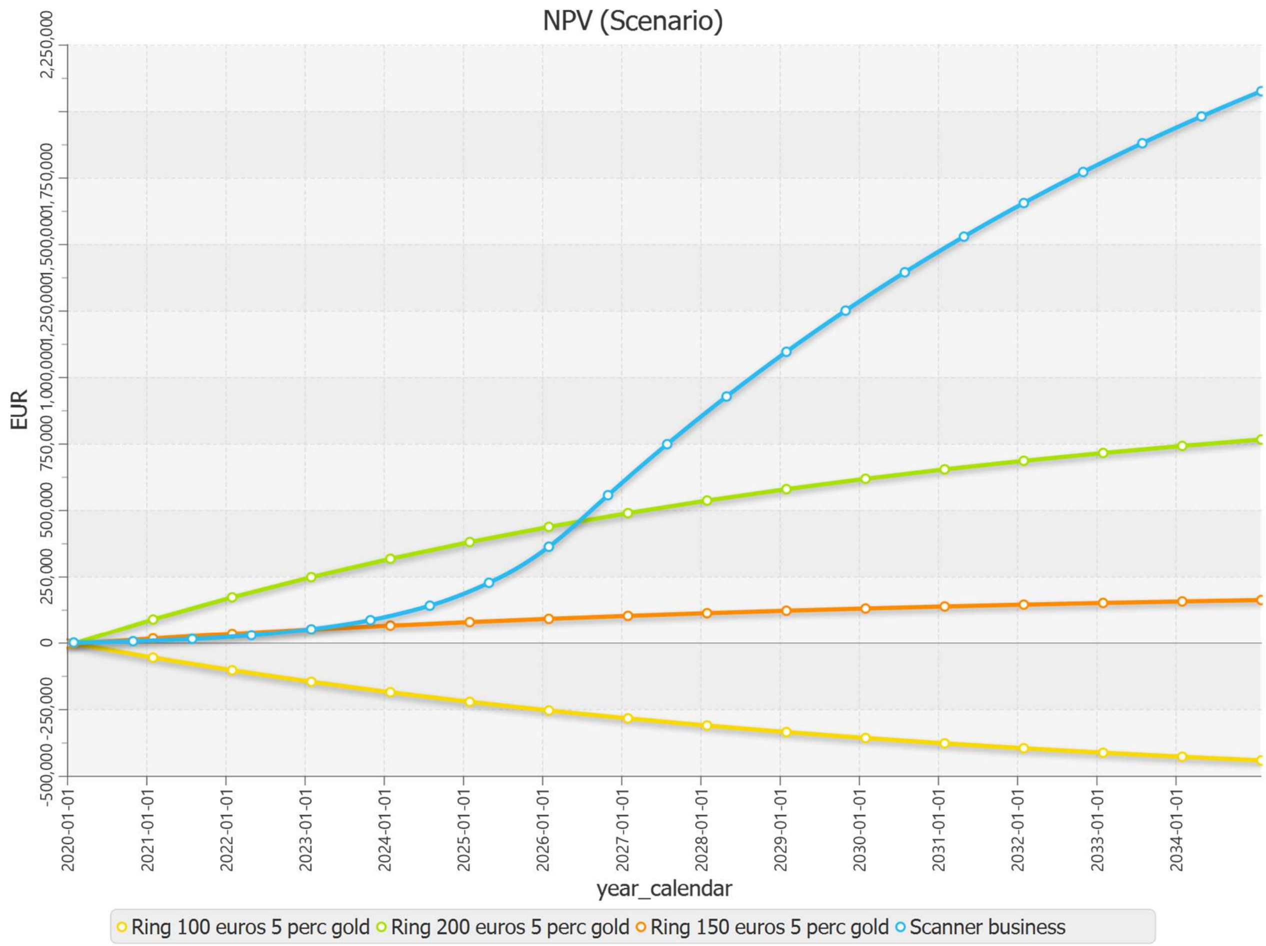
The process starts with the scanning the customer face to define a 3D modell as basis for the casting modell to print with a 3D printer. The form will be filled up with recycled gold to make the jewellery (see the following flow chart).



Identified cost driver: (1) Personal effort (2) Energy costs (3) Logistic costs	**Identified environmental challenges:** (1) Energy consumption (2) Transport costs (printer -> customer)
Assessment model: Fenix_AMMMPS-version02.lcpa	

Key figures and assessment conditions (conservative calculation):

Cost categories	Amount
Retail Price per Scanner	8.000 €
Cost per Scanner (material & assembly effort)	4.000 €
Cost for casting, resin & shipping	37 € per jewelry
Marketing effort	Started with 10.000 € per year
Number of rings sold	Started with 2.400 per year
Share of valuable material	5 %

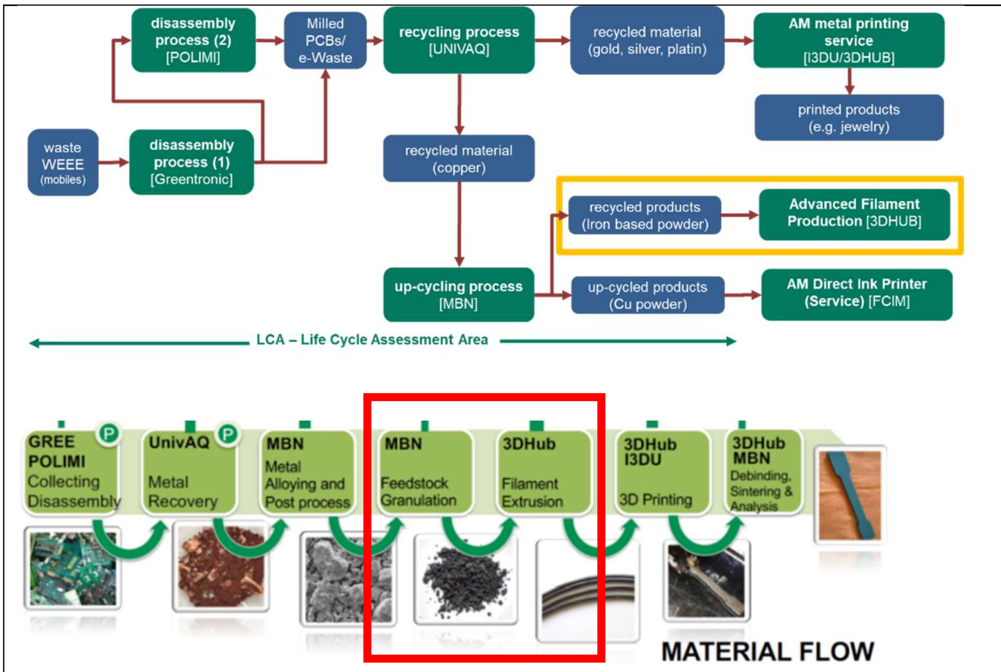


Key findings for the individual jewelry production:

- Raw material price has a high influence on the profitability of business model
- The hardware and operational costs were apportioned pro rata per ring
- The LCC assessment has shown that a selling price of 200 €/ring the product becomes profitable after one year of operation
- 3D Scanner business becomes profitable within the second year

H2020 Innovation Action - This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N. 760792

5.6. Recycling Use Case 3: Advanced filament production



Process goal:

The FENIX filament contributes to lowering the 3D metal printing costs. These costs are very high because of the filament costs but also because of expensive industrial hardware. The FENIX filament should enable 3D metal printing on conventional printers and therfore lowering the costs for 3D printing substantially.

The production of low cost filaments which can be used with relatively low cost hardware and which is reliably extrusion is the goal of use case 3. Using recyled materials based on the circular economy contributes also to greener products in the 3D metal printing artea.

Process description:

The copper based powder produced within the upcyling processes are used to produce filaments for for additive manufacturing processes. The filament granulate is treated in an extrusion process to produce the filament and to sell it on the filament materials market by creating new supply chains.

Identified cost driver:	Identified environmental challenges:
(1) Personal effort (2) Investment costs	(1) Energy consumption

Assessment model: Fenix_MBM v2.lcpa

Steps of the advanced filament production process:

Step	Input material	Main Process	Process result	Weight/ Amount	Energy consumption
1	Iron based powder	-	-	0,4 kg	
2		Feedstock granulation			10,33 kWh [per Kg]
3		Filament extrusion			
4		3 D printing	Printed products		
5		Debinding & sintering	Final printed products		

Assessment Conditions

- Production of advanced filament requires an investment of 150.000 € for debinding, sintering and postprocessing equipment.
- Filament production is closely linked to the upscaling process. The selling prices of the upscaling process results have been considered as purchasing prices for the filament process.
- The filament selling prices will be in the range of 99 € per kilo which is quite cheap for metal-based filament.
- Personal effort is quite low after corresponding automation.
- The market has a high growth potential which is not reflected in the calculation so far.

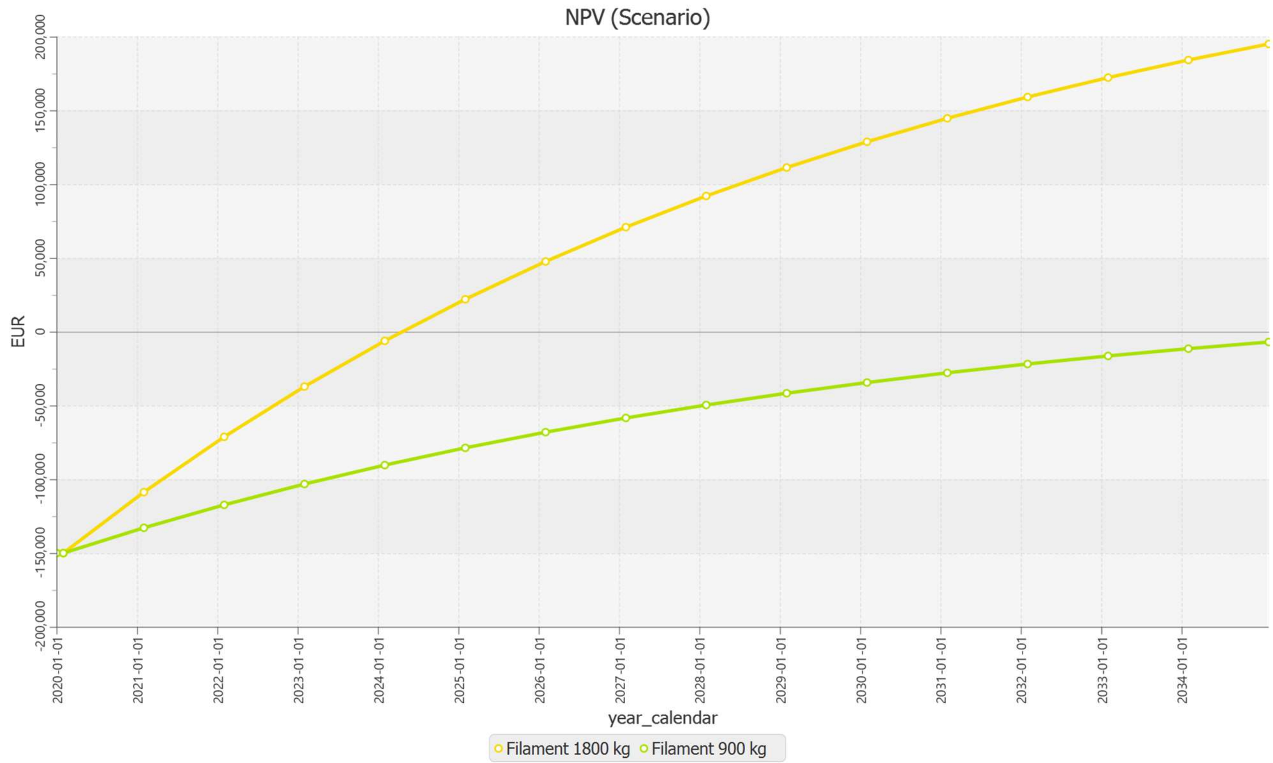


Figure 6: NPV calculation for the advanced filament production

Key findings for the advanced filament production:

- Similar to the upscaling process the profitability of the filament production process depends very much on output quantities.
- The payback time for the yearly production volumen of 1.8 t per year can be realised after 4,5 years.
- To reach also the payback for lower quatities (e.g. 900 kg per year) the equipemnt investment needs to be reduced.
- The market has a high growth potential which is not reflected in the assessment so far.

6. LCA COVERING THE WHOLE FENIX PROCESS CHAIN

The environmental assessment is carried out across all FENIX processes and process chains. The highes impact has the recycling process based on the hydrometallurgical pilot plant. The pilot uses several chemical substances, energy and water in a higher amount than the other processes and terefore dominates the LCA calculation.

The following impact catagories have been selected for the FENIX assessment.

Indicator	Environmental impact category	Calculation
Greenhouse warming Potential (GWP)	Climate Change	GWP [kg CO2 eq.] = 1*CO2 [kg emission] + 25*CH4 [kg emission]
Cumulative energy demand (CED)	Depletion of energy resources	Measured in MWh, Distinguished between fossil and renewable energy
Aerosol formation potential) (AFP)	Damage to human health due to particular matters	AFP [kg PM 2,5 eq.] = 0,5*PM 10 [kg emission] + 0,54 SOX [kg emission] + 0,88 NOX [kg emission]
Acidification potential (AP)	Acidification	AP [kg SO2 eq.] = 1*SO2 [kg emission] + 0,7 NOX [kg emission]
Eutrophication potential (EP)	Eutrophication	EP [kg PO4 eq.] = 0,13 NOX [kg emission]

Table 4: Environmental impact categories in LCPA

The benchmark for the LCA are the conventional mining processes. If not working with recycled materials, the raw materialsoffered by the mining industry would be the alternative.

The most important parameter wihin the ecological assessment is the **GWP (Global Warming Potential)** which describes the contribution of the recycling processes to the global warming of the earth.

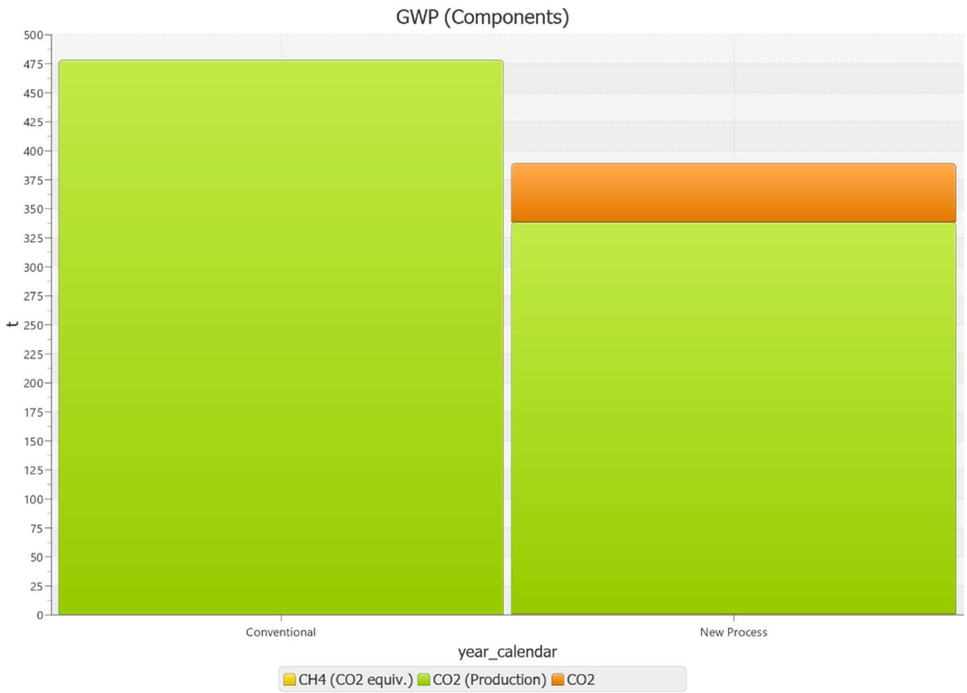


Figure 7: GWP of FENIX processes compared to conventional processes

The new FENIX recycling process include the disassembly part (orange) and the recycling and upcycling processes (green). The FENIX recycling and upcycling processes are **20% better than the conventional mining process** in respect of the GWP.

Another LCA oparameter is the **AFP (Aerosol Formation Potential).** It is used to assess the ability of VOCs (Volatile organic compounds). VOCs are easily become gases or vapors and contribute to the formation of tropospheric ozone and smog.

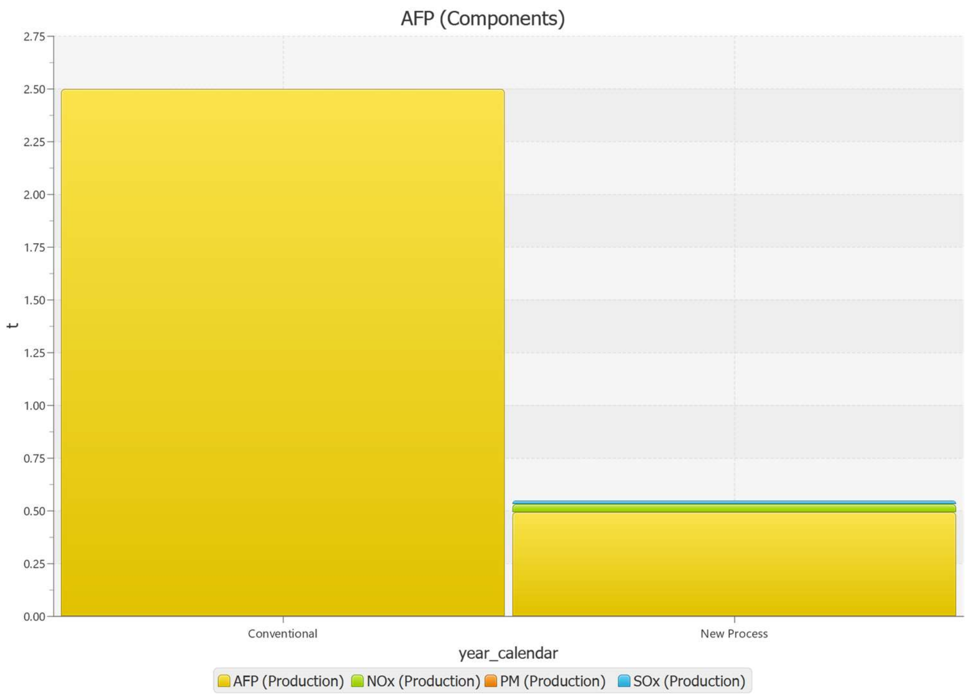
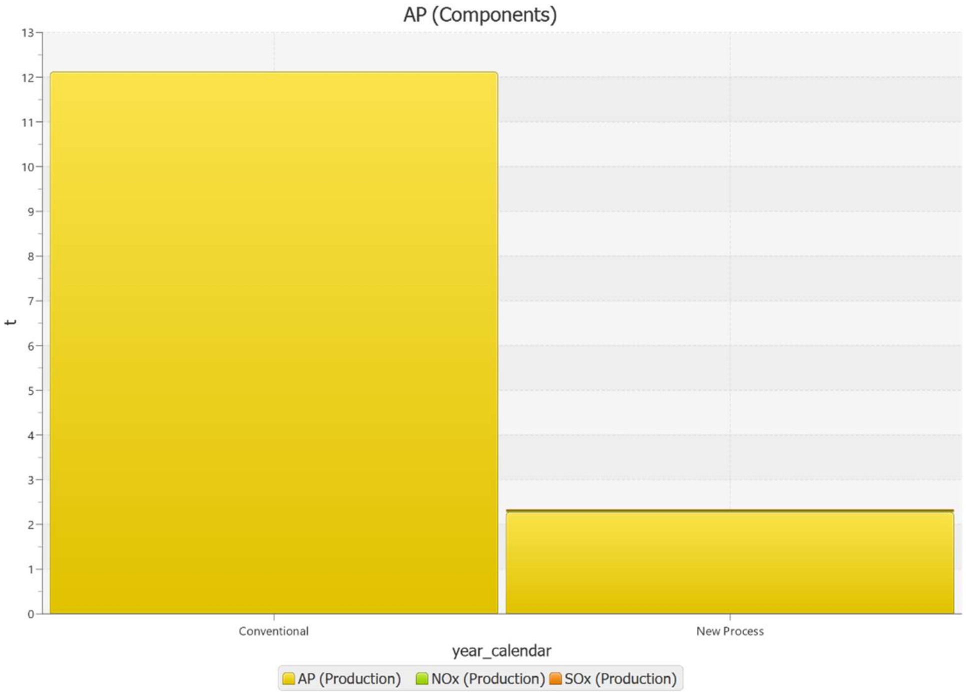


Figure 8: AFP of FENIX processes compared to conventional processes

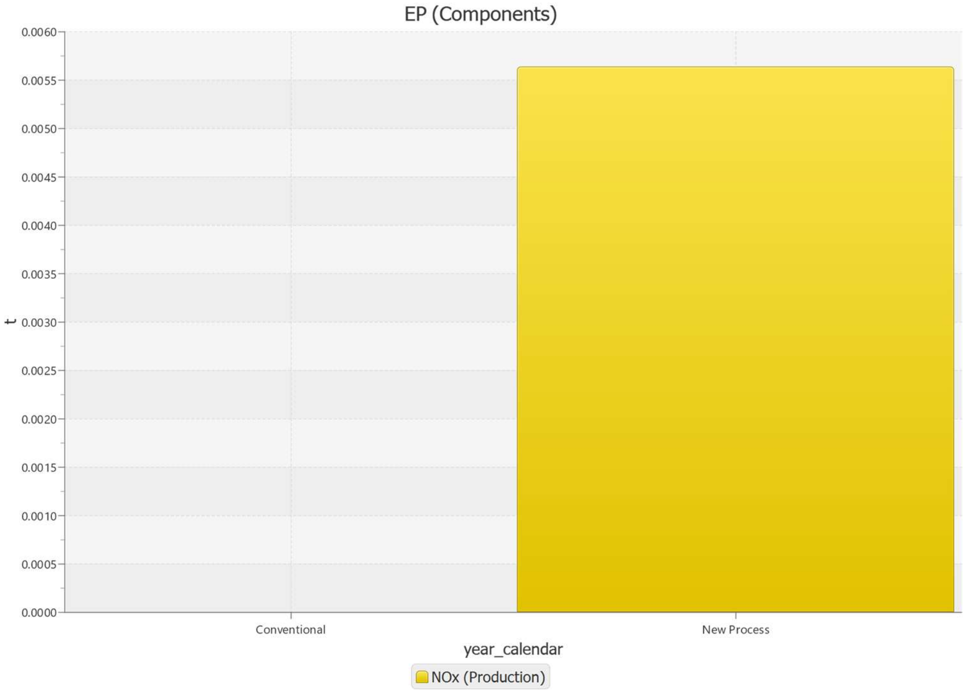
The AFP is where the difference between conventional and new processes is greatest. The conventional mining processes include also NOx, PM (Particle Matters) and SOx, but in comparison to AFP they are no longer shown here. It has to be noted that NOx, PM and SOx together reach a value of 55 kg over 15 years. The AFP of the FENIX recycling process only achieved **20% of the conventional mining process**.

The **AP (Acidification Potential)** increases leaching behavior of heavy metals in soil and has a negative impact on animals and plants



The **FENIX recycling process contributes 80% less** to the Acidification Potential than the conventional mining process and therfore has a significantly lower impact on the health of animals and plants.

Finally the **EP (Eutrophication Potential)** has been assessed. The EP describes the degree of the ecosystem pollution. It shows in which the over-fertilization of water and soil has turned into an increased growth of biomass.



Conventional process generates **no contribution** to EP, while the FENIX recycling process contributes **on a very low level** (5,6 kg). The Eutrophication Potential is the only ecological parameter were the FENIX processes are worse than the conventional processes but on a very low level.

The LCA assessment of the FENIX processes has shown that they are much better and more sustainable than conventional mining. This may have been expected. Nevertheless, the extent of the difference is significantly higher than expected. This argument should become an argument for selling the final products like jewelleries, inks, and filaments. FENIX products can possibly achieve slightly higher margins labelled as a green product.

7. CONCLUSION

The LCPA assessment shows that under the mention conditions every single FENIX process is profitable. The only exception is the disassembly process operated by a Cobot. The investment into the Cobot is quite high compared to the realised operational time (per mobile) and the waste volume available in the project. This makes manual recycling not only cheaper but also much more flexible compared to automated processes.

The economic assessment has considered official market prices for the results (materials, powder, filament) generated by each process. The benchmark for the disassembly process was set at 14 €/kg which is the actual market price for e-waste (PCBs).

Some processes have a harder time becoming economical than others. The hydrometallurgical pilot plant is one of the more difficult processes. The economic efficiency of the recycling process depends on the one hand on the quality of the e-waste (preferably rich material), but also on a corresponding automation degree of the recycling plant. Considering the above-mentioned e-waste prices the breakeven point (revenues necessary to cover all expenses) can be reached after a little bit more than 7 years. This implies reasonably rich material and material selling prices not lower than the actual raw material market prices.

The up-cycling process increases the material value of the recycled material by preparing it e.g. for AM consumable products. These products are copper based powder and iron-based powder to produce filaments. The LCC assessment has shown that the profitability of this process depends very much on the amount of recycled materials. Based on the actual market prices for powder the production capacity should be at least 2 tonnes per year to become profitable in a foreseeable period.

The recycled gold material for the jewellery production is sold to the use case at the market price as basis of the cost assessment. The margin of the previous recycling process is quite low therefore the possibilities for discounting prices are quite low. The jewellery production should use the advantage of an image gain through the processing of recycled gold and should therefore be able to achieve a slightly higher margin on the market.

The ink produced from recycled material took advantage to be used for a specially developed printer. This enables higher margins to be achieved for this kind of ink. This also applies to the filaments for additive manufacturing, which have completely new properties and allow metal printing with conventional printers.

The LCC assessment was supplemented by an LCA to compare the use of recycled materials with the conventional raw materials from mining. This assessment has shown that recycled materials are much better (up to 80%) in nearly all ecological parameters compared to the conventional material.

The most profitable use cases are the ones were the recycled materials can be distributed on the market combined with related products (e.g. jewellery, new generation of printers, etc.). A joint venture of the FENIX process owners would reduce the generated surpluses of each process but would also lower the business risk for some the processes. In summary it would lead to a beneficial recycling process chain with one overall margin and the chance of a comprehensive control over all chain elements.

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