Chapter 7
The Life Cycle Performance Assessment (LCPA) Methodology

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Abstract The FENIX project has started to develop future business models for the efficient recovery of secondary resources. It would not be enough just to improve business models based on traditional linear approaches. Rather, new approaches must be developed with a particular focus on environmental and climate changes. Electronic scrap is no longer scrap, but must be seen as valuable material. Using the mobile phone as an example, FENIX has developed technologies to get recyclable materials out of scrapped mobile phones and to process them into new materials and final products. The developed technological approaches are not limited to mobile phones, but can be used for all types of electronic waste. FENIX has only focused on the logistic chain from the dismantling of the cell phones to the manufacturing of new materials and products (recycling chain). This, of course, involves a lot of effort in dismantling the e-waste, as the recycling process was not yet considered when developing the products currently on the market. Such eco-design approaches would certainly reduce the disassembly effort in the future. FENIX business models should not only be based on economic success but also consider ecological effects at the same time. Therefore, an accompanying Life Cycle Performance Assessment (LCPA) has been carried out to prove the advantages of the developed business models. From the interim assessment, recommendations for further technical development directions were repeatedly given to achieve the best possible economic and ecological solutions.

Keywords Life cycle performance analysis · BAL.LCPA · Circular business models · Key Performance Indicators (KPIs) · Net Present Value (NPV) · Greenhouse Warming Potential (GWP) · Cumulative Energy Demand (CED) · External costs

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P. Rosa and S. Terzi (eds.), *New Business Models for the Reuse of Secondary Resources from WEEEs*, PoliMI SpringerBriefs,
https://doi.org/10.1007/978-3-030-74886-9_7

7.1 Sustainable Business Models

The future of companies, the environment, and society depends on sustainable business models. David and Martin [1] outlined 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.

The treatment of e-waste will get more important for the preservation of natural resources. The FENIX business models are focusing on:

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

In general sustainability refers to four distinct areas: 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. But the approach that continuous growth is good even when it harms the ecological and human environment is becoming less important. New economics approaches 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.

Human sustainability: Human sustainability aims to maintain and improve the human capital in society. Investments in 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.

All four sustainability areas have been considered to create new products from e-waste in FENIX. Nevertheless, the LCPA assessment activities were mainly focused on the economic and environmental aspects [3].

7.2 Electrical and Electronic Waste Market

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].

EUROSTAT (EUROpean STATistical Office) estimates that the second and third largest categories for WEEE (Waste Electrical and Electronic Equipment) collection in the EU comprises around 555 thousand tonnes of 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.

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. In the first approach the FENIX project focuses on the valuable materials of the mobile phones (gold, silver, copper, etc.). But it can easily 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.

Mobile phones are just one example in a high varity of electronic products. Nevertheless it is one of the products with the most valuable materials inside (see Table 7.1). The following table shows the average material content in different product catagories. The FENIX pilot oprations have shown that it can differer very much from batch to batch. Therefore the values can only be used as guidelines. The large amount of material to be expected in a mobile phone was a reason to choose these items. During the assessment of the different FENIX processes it has been shown

Table. 7.1 Characterization of metals embedded in specific WEEE

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

Source Cucchiella et al. [4]
Remark: 0.2% of Au means 200 g of Au in 1 ton of PCBs

that the material composition of the e-waste has an high impact on the economic efficiency of the examined processes.

7.3 Life Cycle Performance Assessment (LCPA) for FENIX

The ecological awareness of customers is increasing in Europe. The FENIX project has started to improve the recycling processes and to make better use of electronic waste using cell phones as an example. The project has focused on the optimization of the recycling processes and process chains starting from disassembly up to the production of recycled materials and products.

Different approaches and technologies for disassembly, recycling, and up-scaling of recycled material have been tested. These FENIX 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 implemented 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 jewelry 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 compare the different approaches and technologies developed by FENIX and to verify the economic viability as well as the ecological impact an LCPA (Life Cycle Performance Assessment) has been performed. The Life Cycle Performance Assessment (LCPA) includes the Life Cycle Assessment (LCA) with the focus on the ecological impact and the Life Cycle Cost analysis (LCC) considering the economic calculations [5].

The LCA is defined as compilation and evaluation of in- and outputs (e.g., use of natural resources, emissions to air, water, and waste) and the potential environmental impacts throughout its life cycle. The LCC approach has been used to analyse the economic perspective by applying the Net Present Value (NPV). The NPV is calculated by a dynamic procedure and considers the current value at each time which means that earlier revenues are valued higher than later ones. To prove the profitably, the calculation of the net present value is essential.

The most important KPIs (Key Performance Indicators) have been defined in cooperation with the different FENIX process owners (disassembly, recycling and up-cycling) (see Table 7.2). LCPA results base on a combination of various KPIs including life cycle costs, Global Warming Potential and the cumulative energy demand.

For the FENIX assessment the following Key Performance Indicators (KPIs) have been selected from a larger set of parameters.

The assessment bases on complex mathematical models. To carry out the LCA and LCC assessment in parallel the commercial LCPA tool from BALance (BAL.LCPA)

Table 7.2 KPIs selected for the FENIX assessment

Focus	KPIs	Description
LCA	Amount	Amount of materials used in in the recycling process
	Raw material to process	Indicate the materials involved like e.g. metals, minerals, plastics, textile, organic and 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)
	GWP	Greenhouse Warming Potential → Climate Change
	CED	Cumulative energy demand → Depletion of energy resources (distinguished between fossil and renewable energy)
	AFP	Aerosol formation potential → Damage to human health due to particular matters
	AP	Acidification potential
	EP	Eutrophication potential
LCC	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

has be applied to support a comprehensive decision-making process for process alternatives already in the early development phase of the project.

Therefore, assessment models for the different FENIX areas have been defined and were implemented in the BAL.LCPA tool. The models include the descriptions of the operational processes but also reference processes to be able to compare different approaches. The models were supplied with estimated values and later with actual measured values generated by the installed pilots to ensure realistic statements. For the FENIX pilots a screening LCA has been applied to focus on the most important environmental challenges.

The BAL.LCPA software 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 visualized 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.

7.4 Assessment of FENIX Implementations

The Life Cycle Cost analysis has been carried out for each process and the interconnections of the processes. The assessment has been divided into the processes (disassembly, recycling, and upscaling) and the product related use cases (metal powder and robocasting, jewelry production and advanced filament production). After the optimization, a comprehensive assessment was carried out. 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.

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 results are summarized within this chapter.

The assessment starts with the disassembly process. FENIX is not focusing on the e-waste collection process while the improvement potentials under FENIX main emphasis is very low compared to the conventional processes of today (Fig. 7.1).

The focus of the disassembly process is to dismantle the mobile phone scrap in an environmentally friendly and cost-effective manner. Poor manual disassembly processes have been assessed as well as COBOT (COllaborative RoBOT) supported manual processes. 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. The disassembly assessment results can be briefly summarized in the following points:

- Poor manual driven disassembly processes are beneficial after a short time (months) while the duration depends mainly on the salary rate of the personal.
- Disassembly processes based on COBOT operations (manual plus robot) are too expensive under all circumstances and become never beneficial. The reasons are the high process time per mobile phone for the COBOT and the hardware investment costs.

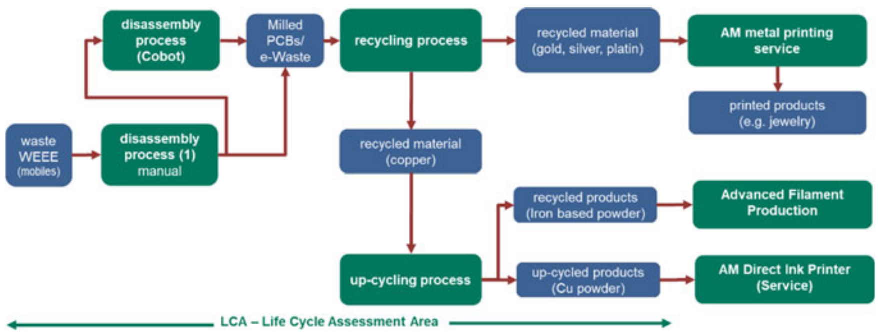

Fig. 7.1 Life Cycle Assessment area

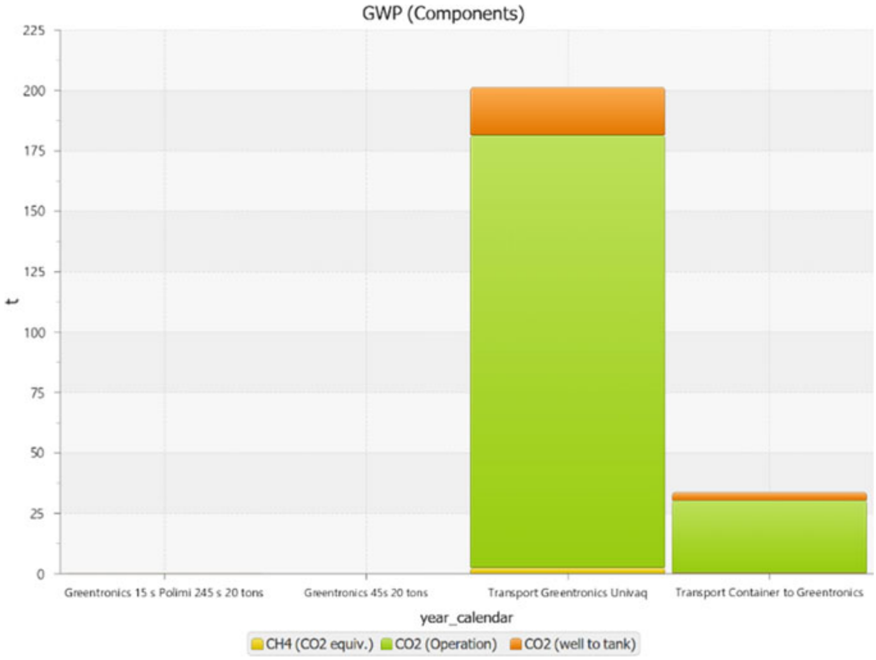

Fig. 7.2 CO_2 emissions

- Transportation costs have been calculated based on the manual disassembly process. Their influence on the NPV is very low over the evaluated period (15 years) so that it can be neglected.
- Transportation has an important influence on the GWP (Green Warming Potential) as shown as part of the LCA analysis (Fig. 7.2).

One challenge of the FENIX project was the development of a mobile recycling plant (recycling reactor in a size of one container). This makes it possible not to bring the e-waste from the disassemble service provider to the recycler, but rather the recycling process to the disassembly provider. This approach reduces the logistical effort. But it also assumes that the disassembler has enough material available to use the system for a certain period.

For the evaluation of the logistic processes the real distances between the disassembly and the recycling location have been considered as basis for the assessment. 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.

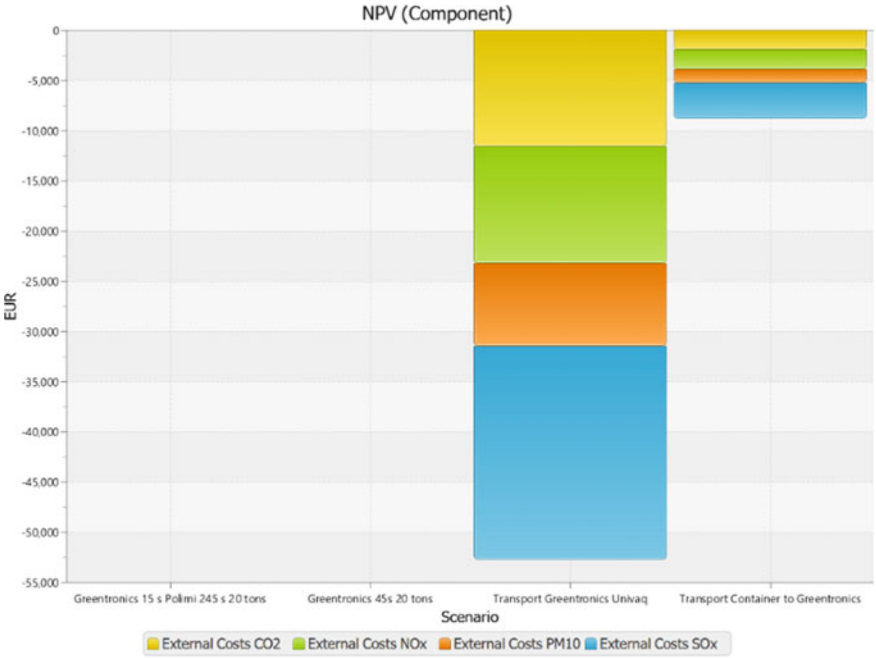

Fig. 7.3 External costs

- 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.

The following figure shows the results of the external cost assessment based on transportation (Fig. 7.3).

The main goal of the recycling process is to remove as much valuable material as possible from the e-waste prepared by the disassembly process. The hydrometallurgical pilot plant developed within the FENIX project should assure an environmentally friendly and cost-effective recycling process. The pilot installation has been focused mainly on the generation of gold, silver and copper as basis for the assessment. But other materials could also be extracted with the same unit in the future.

The recycling process assessment results can be briefly summarized in the following points:

- The semi-automated material recovery plant operated in two shifts will not become beneficial (yellow curve in the following figure). The semi-automated process was installed in the first development step of FENIX, but it became clear very quickly that a higher automation degree for the plant is required.

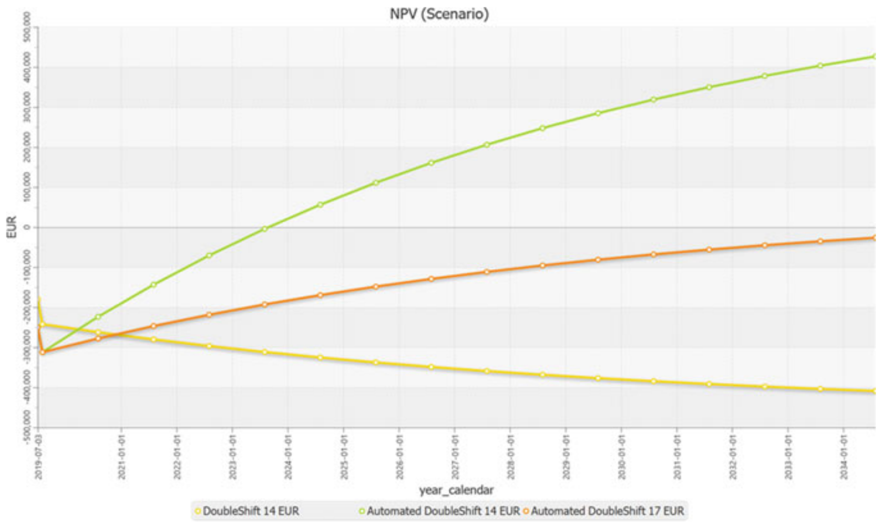

Fig. 7.4 Overall NPV scenarios

- The automated material recovery plant will become beneficial after 5 years considering the actual PCB purchasing market prices (price of the incoming e-waste).
- The sensitivity analysis for automated material recovery plant has shown that the increase of the PCB purchasing price of 10% extends the duration to 14 years before becoming beneficial. This shows the high impact of the e-waste PCB price on the economic efficiency of the process.
- Richer e-waste materials would shorten the time significantly.
- The assessment of the recycling process bases on a yearly process volume of 20 t/year (PCB waste). This volume can be achieved with a container-based reactor. Turning away from the container approach would lead to a higher process volume and thus to increase the profitability (Fig. 7.4).

The upcycling process is a preliminary stage to refine copper from the FENIX recycling processes to produce copper-based powder. This metal powder is the basis for the ink production (FENIX use case 1: Direct Ink Writers) and the production of advanced metal-based filaments (FENIX use case 3). Additionally, the metal powder should be directly sold to the market for e.g., laser metal deposition and sintering.

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.

The upscaling process assessment results can be briefly summarized in the following points:

- Profitability of the upcycling process depends very much on the output quantities. Official market price for copper and additional materials have been used for the assessment.
- A minimal material output of 2 t per year and a much lower personal effort (industrial production) will assure a payback time after 8.5 years. So far, the production has only assessed on a laboratory level with a small amount of material and a high personal effort).

Looking only at the processes (disassembly, recycling and upscaling) the assessment results show that the profits are associated with different risks. This includes the market prices for e-waste and raw materials (to sell) as well as the production capacity. The processes are only profitable from a certain amount of material that must be sold on the market. To reduce the risk FENIX has also focused on products produced from recycled FENIX materials within the three use cases.

The metal powder and robocasting use case consists of the development of DIW (Direct Ink Writing) printers for high precise printings (robocasting). The DIW is a 3D-Printing technology which a paste-like filament is extruded from a small nozzle. The nozzle moves across the printing table. The new DIW developed by FENIX 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 (Fig. 7.5).

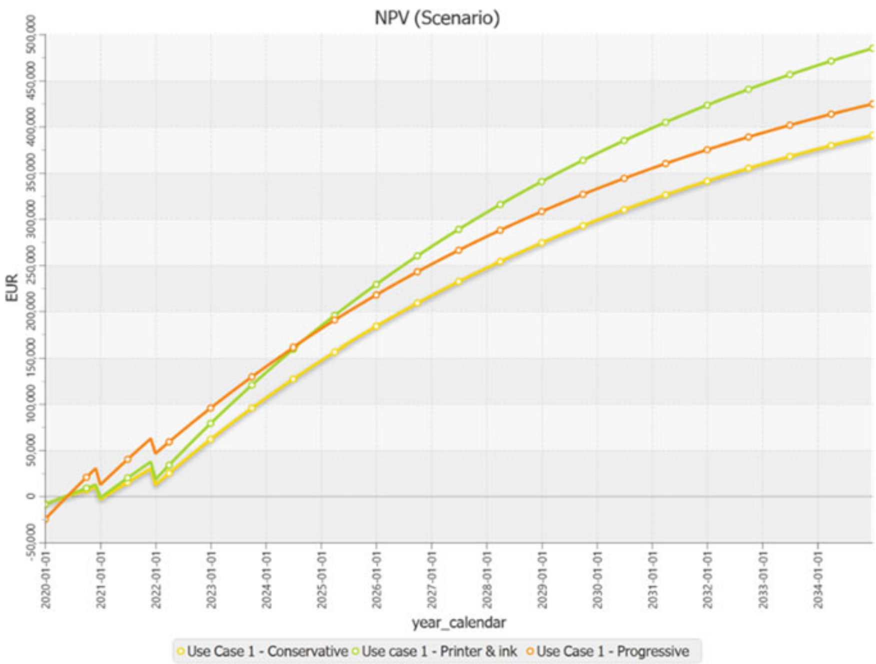

Fig. 7.5 Use case 1 NPV scenarios

Beside the development and the marketing of the printer, FENIX has developed and produced ink for the DIW printers from the materials of the FENIX upscaling process. This special ink has been optimized to enable lower sintering temperatures for the printed products. This means that smaller sintering furnaces with lower energy requirements can be used.

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 and promises higher margins.

The metal powder and robocasting use case results can be briefly summarized in the following points:

- The sale of the printers and the associated special ink generated from recycled material promise to be a success story. However, it must be considered that this is a new product for which only limited market figures are available.
- By the combined marketing of ink and printer the income is much higher than for recycled material. Different scenarios have been calculated (see figure). For the conservative scenario with an amount of 3 sold printers plus ink the use case becomes beneficial after one year.

The jewelry production use case has been started to use the valuable materials of the FENIX recycling process (gold, silver, etc.) to produce personalized jewelries. It is expected to generate higher margins (compared to simple recycled materials) by creating sustainable products through personalization and the use of recycled materials.

Therefore 3-D face scanners have been developed within the FENIX project. These scanners will be sold to jewelry stores for scanning the customer face to define a 3D model. This model is the basis for the casting model to print with a 3D printer. The form will be filled up with recycled gold or other valuable recycled material to make the jewelry (face on a ring, etc.). The use case is separated into the development and production of face scanners for the personalization and the production of jewelries and the FENIX jewelry printing service.

The metal powder and robocasting use case results can be briefly summarized in the following points:

- Raw material prices have a high influence on the profitability of business model.
- 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.

The FENIX filament production use case contributes to lowering the 3D metal printing costs. Today, 3D metal printing cost are very high because of the filament costs but also because of expensive industrial hardware. The FENIX filament enables 3D metal printing on conventional printers and therefore lowering the costs for 3D metal printing substantially. Low-cost metal filaments which can be used with relatively low-cost hardware and which is reliably extrusion is the competitive advantage of the FENIX filament produced from recycled materials.

The filament production use case results can be briefly summarized in the following points:

- Similar to the upscaling process the profitability of the metal filament production process depends very much on output quantities.
- The payback time for the yearly production volume of 1.8 t can be realised after 4.5 years.
- To reach the payback for lower quantities (e.g., 900 kg per year) solutions have to be found to reduce the equipment investment costs.

The most profitable use cases are the ones were the recycled materials can be distributed on the market combined with related products (e.g. jewelry, 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 the previous processes (disassembly, recycling, and upscaling). 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.

7.5 LCA Assessment of the FENIX Processes and Use Cases

The environmental assessment is carried out across all FENIX processes and use cases. The highest 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 therefore dominates the LCA calculation. The following parameters have been selected for the FENIX assessment.

- Greenhouse warming Potential (GWP)
- Cumulative energy demand (CED)
- Aerosol formation potential) (AFP)
- Acidification potential (AP)
- Eutrophication potential (EP).

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

The most important parameter within the ecological assessment is the GWP (Global Warming Potential) which describes the contribution of the recycling processes to the global warming of the earth (Fig. 7.6).

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. The AFP (Aerosol Formation Potential) 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 (Fig. 7.7).

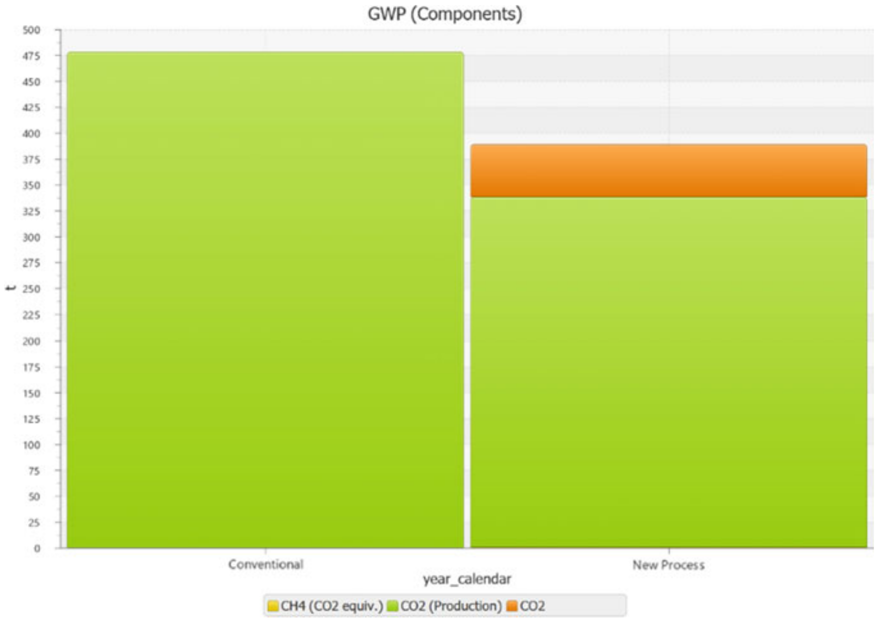

Fig. 7.6 Comparison of CO_2 emissions

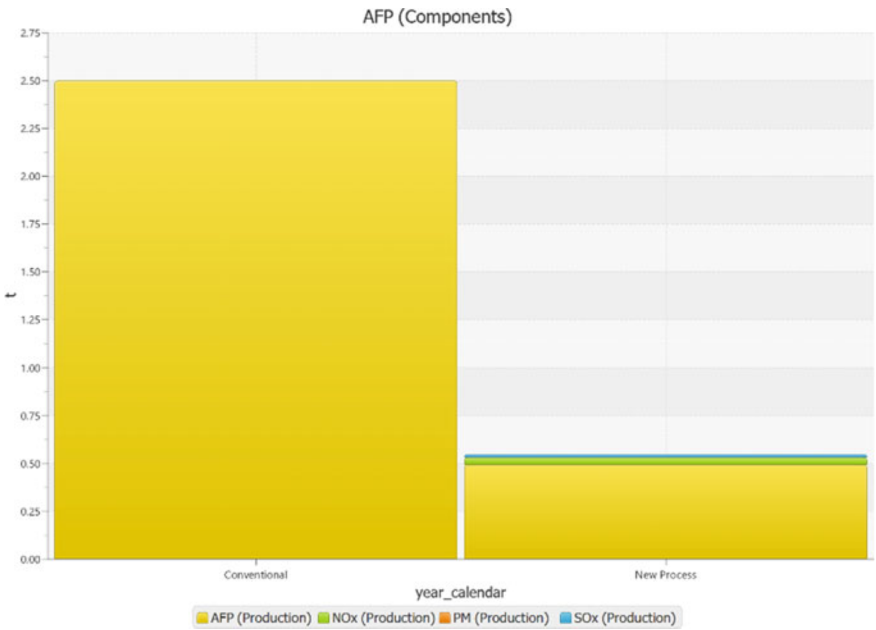

Fig. 7.7 Comparison of other emissions (1/2)

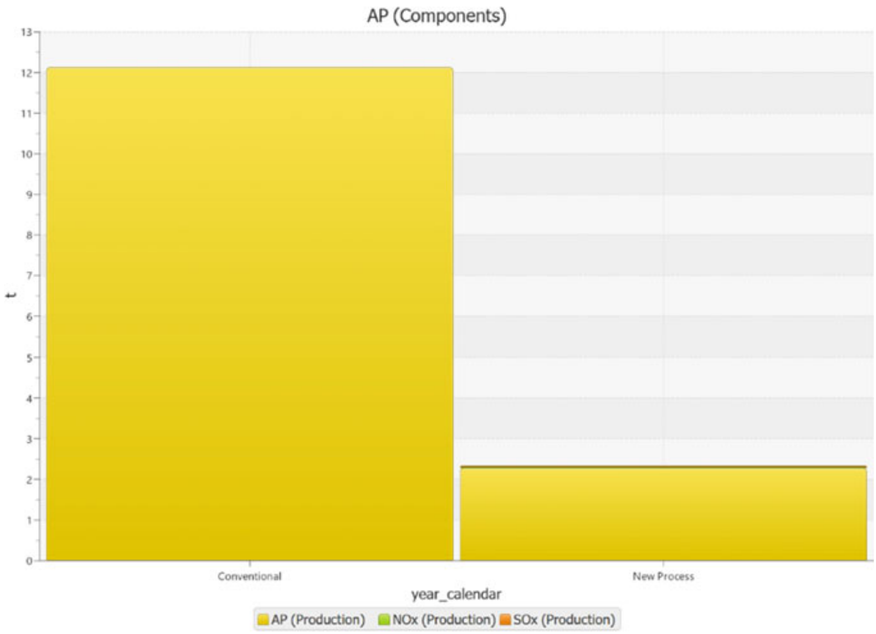

Fig. 7.8 Comparison of other emissions (2/2)

The AFP shows the greater difference between conventional and the new processes. The conventional mining processes include also NOx, PM (Particle Matters) and SOx, but in comparison to AFP they are no longer shown in the following figure. 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 accounts for 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 (Fig. 7.8).

7.6 Conclusions

The FENIX recycling process contributes 80% less to the Acidification Potential than the conventional mining process and therefore has a significantly lower impact on the health of animals and plants. The EP (Eutrophication Potential) 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 processes generate no EP, while the FENIX recycling processes have a very small share (5.6 kg). The Eutrophication Potential is the only ecological parameters were the FENIX processes are worse than the conventional processes but on a very low level. The LCA in FENIX compares 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. This fact may have been expected. Nevertheless, the extent of the difference is significantly higher than expected. These assessment results can be used to sell the final products like jewelleries, inks, and filaments as green products with higher margins.

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