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Industrial hazardous waste treatment: life cycle assessment of an innovative process for material recovery

Experimental degree thesis

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Abstract

The knowledge of a product's life cycle is essential to study the environmental impacts and the possible solution to them, and so is its end-of-life. Nowadays many products can be recycled, and technologies keep moving forward to help the process.

Waste is not just waste, scrap to landfill or incinerate, from it can be possible to recover some material that can be reused in our daily life or in the industry.

The scope of this Thesis is to explore and investigate the possible environmental impacts of a different pathway, an innovative procedure that differs from the traditional one.

One of the most frequently used methodologies to make the environmental assessment of a product, process or service is the so-called “life cycle assessment” (LCA). This methodology uses the environmental impacts that are associated with a product or a process considering the entire life cycle.

The innovative scenario introduced is peculiar because it helps with material recovery too and not just with thermal energy recovery, like a business-as-usual scenario. Of course, for the material recovery, the hazardous waste introduced inside the process needs some modification, a leaching process is added to make copper and aluminium precipitate and then become the avoided product and significantly lower the total environmental impact.

The study was made with the use of SimaPro software that helps to generate the models. At the end of the Thesis, some added analyses were explored: sensitivity and uncertainty. Those helped to investigate different scenarios and compare the traditional with the innovative.

Summary

1 Aim of the study

The project considered in this Thesis intended to study the environmental applicability of new technology (on an experimental scale) to reduce the quantity of waste disposed of, increasing at the same time, the potential recovery of valuable materials.

Life Cycle Assessment (LCA) method was used to investigate the environmental applicability, in this case study an innovative scenario is treated.
The innovative scenario considered has as input the hazardous waste stream originated from the final treatment of a metal process’s recovery. This residue, for its nature, cannot be landfilled and need a different process that will end with incineration. In the innovative one, a different approach will be shown, and an additional metal recovery will be added. At the end of the study, a comparison between a generic traditional scenario and the innovative one will be displayed.

The application of LCA methodology helps not just to provide full comprehension and quantification about the environmental impacts related to the system is also performed to obtain different information from the process. For the modulation phases of each scenario, the software SimaPro version 9.4.02 Ph.D and the database ecoinvent 3.7.1 were used.

2 End-of-life treatment

”The instruments requested from the European community to enter in a few years in a “Europe of Recovery” are getting more and more in the application research, in the economical instruments that take advantage in the passage from one technology to another, but also in the education and formation in all levels: social, cultural, and productive.
“Sustainable use of natural resources and waste management” as a business to mark the Sustainable Development of Waste recovery, in which the keywords are linked with different fields of research such as the Integrated Management System, the Re-Products, Dematerialization of commodities, Eco-efficiency of processes, Closed Loop Economy, Eco-design.
The Economic/Industrial system that interacts with the ecosystem, as said by the principle “More with less” (Broundtland ’87 “Our common future”), needs to be self-sustained by reducing the consumption of energy and raw materials that come from the environmental system, to enforce the production of goods and services, save on consumption, reduce the impact on the ecosystem. The Culture of Responsibility, facing the world's crisis, asks the people to consider procedures; social, political, and economic behaviours, to try to limit or avoid the crisis. If all these concepts about new technology, already announced by the Best Available Techniques, are not mediated through a language that influences individual and collective behaviours, the most effort would be in vain.”
-Prof. Luciano Morselli – “L’Europa del recupero con una rinnovata Cultura della Responsabilità” (1)

2.1 What is the end of life of a product?

Wastes are any materials that are not the prime product for which there is no further use for purpose of production, transformation, or consumption and that are required to be discarded (Council Directive of 15 July 1975 on waste (75/442/EEC) (2).
The end-of-life (EoL) of a product, in its life cycle, is the final stage of a product’s existence. The concern about end-of-life depends on the perspective and type of goods (their use and function, for example, if it is special or hazardous, its recyclability, etc.) and whether the waste treatment is extended to the producer (Extended Producer Responsibility – EPR (3)) or depends on the community. For the manufacturer, end-of-life is not only about discontinuing production but also following the market needs. For the final user (business or private), EoL includes the disposal of the existing product, transitioning to a different product if possible and ensuring that disruption will be minimal.

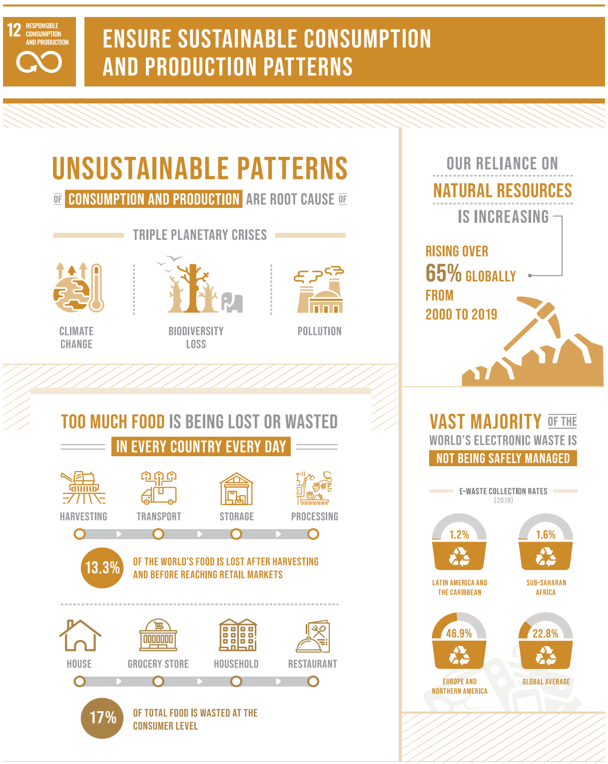
Nowadays waste management is part of the core of society’s strategy for the adverse effects of its activities. For its complete system approach, life cycle assessment (LCA) is frequently used as a powerful tool for the assessment of waste management activities. However, it is not easy to understand completely the correct strategy for waste treatment, and many methodological aspects regarding the environmental assessment of waste treatment systems are still far from being considered standardized, such as system boundaries (temporal), life cycle inventory (LCI), use of environmental indicators, analysis, and interpretation of the LCA results (4).

Even though the correct treatment of waste needs to be part of the central decision in the present society, it is still difficult to find the correct technology to treat some waste flows and their management results hard.

The 17 Sustainable Development Goals (SDG), proposed within the *Agenda 2030*, deal with different aspects of social, economic, and environmental development, which should be considered in an integrated and fulfilled manner, with all the processes that help in a sustainable way, including the international cooperation and the political and institutional background.
In the 17 SDGs, there are references to human health and to an equal distribution of development benefits. Each goal has an objective to arrive at in the next years (5).
Within the Sustainable Development Goals, the Goals and indicators addressing waste issues include:
11.6.1: Municipal Solid Waste Management
12.3.1: Food Loss and Waste
12.4.1: Information Transmitted under Chemicals and Waste Conventions
12.4.2: Hazardous Waste generated and treated
12.5.1: National Recycling Rate
14.1.1: Coastal Eutrophication and Plastic Debris Density

Of course, different types of waste management are considered, with the indicators, in the 17 SDGs.

Below is an infographic of the Goal 12. This is a resource- and waste-management oriented, and it considers the waste products from food to hazardous chemicals.



THE SUSTAINABLE DEVELOPMENT GOALS REPORT 2022: UNSTATS.UN.ORG/SDGS/REPORT/2022/

Figure 2.1 *12 Sustainable Development Goals infographic. Taken from (5).*

“12.4 By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment.” – 12 Sustainable Development Goals Indicators, United Nations.

The 12.4 indicator refers to the number of Parties: countries that have ratified, accepted, approved, or accessed, the Multilateral Environmental Agreements (MEAs). This includes:

- Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (6).
- Rotterdam Convention on the prior informed consent procedure for certain hazardous chemicals and pesticides in international trade (7).
- Stockholm Convention on Persistent Organic Pollutants (8).
- Montreal Protocol on Substances that Deplete the Ozone Layer (9).
- Minamata Convention on Mercury (10).

The indicators’ focus is on the obligations that contribute to the overall environmental management of chemicals and wastes, studying their life cycle (11).

2.2 Waste and the Environmental Impact

When there are any changes to the environment this is called: environmental impact, whether adverse or beneficial, and it can be from a facility’s activities, products, or services.

When we talk about waste, it can generate a negative impact, for example during the process of incineration, if the pollutants are left free in the atmosphere. On the other hand, a positive impact could be generated the production of a new material occurs from pre-consumer and post-consumer scraps (a sort of circularity in the original product).

Europe generates large amounts of waste: food to garden, construction and demolition, mining, industrial, electronics, etc. This amount always changes, and with the demographic changing every day and the spectrum of waste too (including illegal waste), it is not possible to study a complete overview of the waste generated.

The EU Data Centre on Waste (12) compiles waste data at the European level. According to a 2020 evaluation, of 29 European countries, around 60% of the waste generated consisted of mineral waste and soil, largely from construction and demolition activities and mining. The following categories range from 1% to 10% of the total: *i)* metal, *ii)* paper and cardboard, *iii)* wood, *iv)* chemical and medical waste and *v)* animal and vegetal wastes.

Around 9.4% of the total waste generated in Europe consists of what is known as ‘municipal waste’.

Through the years was observed a slow increase in the EU pollution generated from municipal waste, this was possible with tight legislation regarding waste management. In the EU an increasing amount of waste is recycled, so, a decreasing amount of it is landfilled. From 2004 to 2020 the amount of recovered waste in EU-27 increased from 45.9% to 59.1%. The share of disposal in total waste treatment decreased from 54.1 % in 2004 to 40.9 % in 2020 (12).

This shift in waste management is linked to EU legislation. The key is the Waste Framework Directive (WFD) (13). This directive outlines a waste hierarchy: starting with prevention, re-use, recycling, recovery and, at the end, disposal.
The WFD works along with other EU directives containing targets. Countries can adopt different approaches to reach them.

The direct negative impact of non-adequate waste management is climate change and ecosystem contamination (on air, water and soil), which will also affect biodiversity and human health.
Landfills, considered the final destiny in the waste hierarchy, contribute to the release of methane (due to the organic substances dumped). Landfills may also contemn soils and water because of chemical leakages.

Wastes are collected and then treated. The transportation process (between collection and treatment) contributes to the release of CO_2 and other air pollutants, including PM that goes into the atmosphere. At the same time, it provokes resource depletion (i.e., fossil fuels).
Part of the waste collected might be incinerated or recycled. The energy produced from waste (after incineration) can be used to produce heat or electricity, and this can be a good replacement for using coal or other fossil fuels.
One of the most helpful strategies is recycling. It can help even more to lower GHGs. When the usage of recycled materials increases, there is less extraction of raw materials. Anyway, waste affects the environment indirectly. When something is not recycled it will be a loss in raw material.

Waste affects our health. The toxicity of some pollutants is well known and is one of the main reasons to try to reduce them.

In conclusion, waste management costs money. Creating all the infrastructure and recycling structure is costly, but once done it can generate work for people and reduce the use of raw materials (14).

2.3 Circular economy for waste

In the economy we are living in, extracting materials from the Earth is a consolidated practice, such as making products and eventually throwing them away. This form of economy is well-known as linear.
In a circular economy, on the opposite, we stop waste ad we use it as new-raw material. We stop waste from being produced (15).
The circular economy is based on three principles, driven by design:

- Eliminate waste and pollution
- Circulate products and materials
- Regenerate nature

Extracting fewer materials and using existing ones would help to lower some impacts. By 2020 one of the key objectives of the EU was turning waste into a resource, this report was written before Covid-19 that changed the perspective written in this paper.

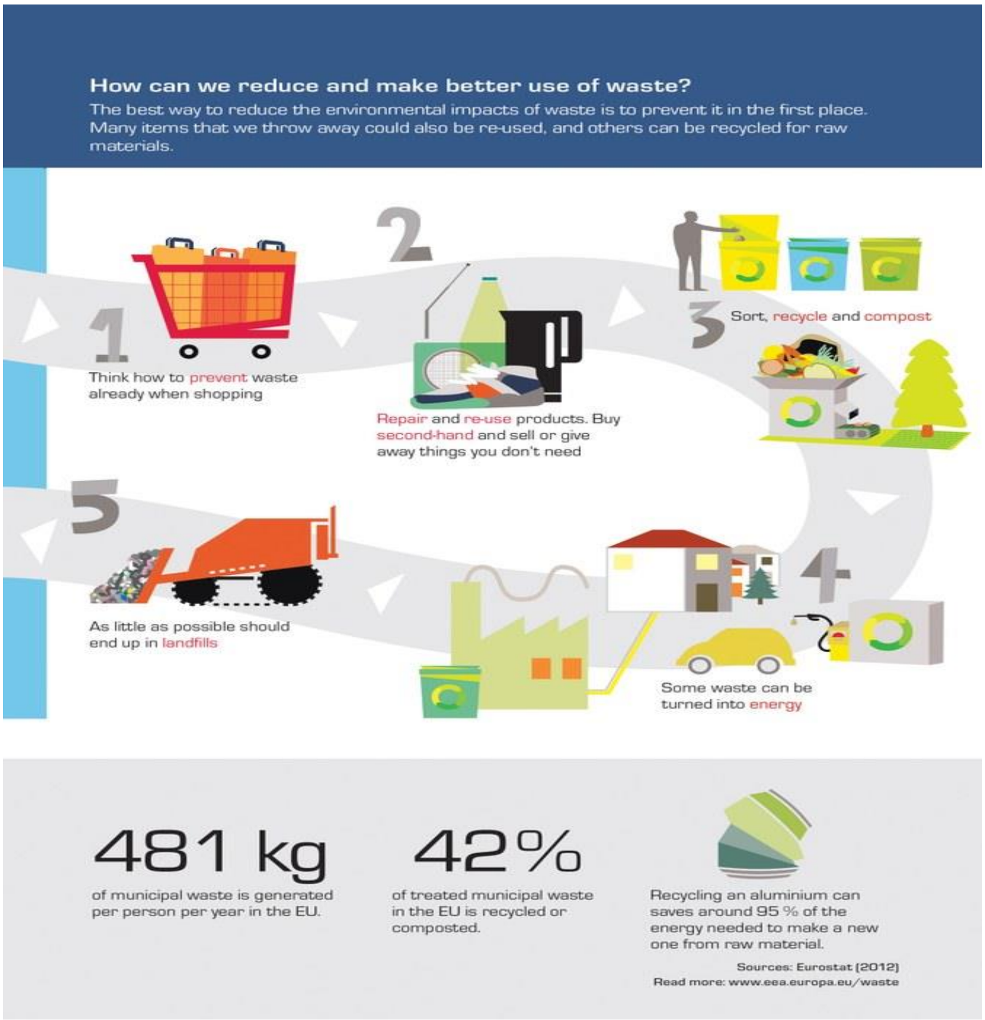


Figure2.2 *How can we reduce and make better use of waste? Taken from (5).*

2.4 Waste management in end-of-life vehicles

Waste management is not easy, especially that applied on vehicles. Directive 2000/53/EC sets a goal of 85% material recycling from ELVs (end-of-life vehicles) by the end of 2015. In 2011, the year of the case study taken as an example - *Auto shredder residue recycling: Mechanical separation and pyrolysis* – the recycling rate was 80%.

The 20% apart from the recycled part, also called automotive shredder residue (ASR), in Europe, is manlily landfilled, since considered hazardous and contaminated. Literature has shown how pyrolysis could help as starting point for the “waste-to-chemicals” perspective, of course further study needed to be done to reintroduce this chemical into the industry (16).

In this Thesis, there will be the exploration of a new methodology that hopefully will help to give a new life to a part of this hazardous waste.

3 Italmetalli S.r.l. - Fiori Group

Italmetalli S.r.l. (Italmetalli), located in Valsamoggia (Bologna district), is part of the Fiori Group (Fiori Metalli S.p.A.), a company founded in Bologna in 1952 by Ferrante and Otello Fiori. The two brothers distinguished themselves as the collector of iron and non-iron materials that could be reutilized as raw materials in heavy industry (1). In fact, after World War II, Italy was a devasted country, reconstruction began and the need for raw material was essential, nothing could be wasted. It was at this point that the peasant culture of reuse and recycling, typical of this territory, was naturally transferred to the activity of reuse and recycling of metal.

Figure 3. 1 *- Fiori's Family in 1948, the beginning of the company (1).*

From that difficult growth year, the group begin an entrepreneurial expansion next to other sector companies, starting to be a reference point and giving a strong developing contribution.

The improvement of this business could be possible for some reasons: the entrepreneurship passed from generation to generation, the professionality that follows the name “Fiori”, the technical expertise and finally the endless determination to always find new technologies without losing their human perspective and relationship.

Furthermore, the continuous research with new solutions leads the company to new goals such as economic development and the safety of the environment and workers, ensuring customer satisfaction and, more in general, of the stakeholders.

Today, with more than 70 years of experience, Fiori Group is a solid reality. Italmetalli manages everything in the sector of metals recycling, from scrap collection to shredding up to the supply of the material.

The activity is characterized by an industrial cycle that starts from the purchase of metal waste and then, with new techniques from the R&D unit’s constant development, it can produce “new raw-second material” with iron, inox, copper and aluminium to be used inside a second industry to produce half-processed and finished products.

Figure 3.2 *- Crespellano, Italmetalli S.r.l (1).*

Moreover, Italmetalli is a platform of the “Consorzio RICREA” that gives value to the metal packaging from the separate collection waste: this material passes from the stage of waste to product, and it could be possible to reintroduce it as a raw material in the steelworks.

All the working phases are managed following a complex integrated management system, regulated by ISO 9001, ISO 14001, and ISO 45001 (quality, environment, and safety), UE regulations n. 333/2011 (stop of waste status for iron, inox and aluminium) and n. 715/2013 (stop of waste status for copper and its alloys) and RINA certificate (that certifies that the quality management system of Italmetalli is in compliance with the standards ISO 9001:2015 for waste recovery of metal: iron, steel and aluminium), from the national system Accredia, the Italian accreditation body.

Fiori Group's core business is represented by the metal’s recovery. However, the research and development team are right now looking for maximizing the recycling process beyond metals, focusing attention on all the input materials. Some examples are plastics and inert (glass).

In addition, the activities in which Fiori Group is involved are:

- Work, selection, transformation, and commerce of ironing material and non
- Commerce and intermediation of iron waste and non
- Manage and realization of waste and recovery treatment
- Land, sea, rail and air shipment, transportation of the product, wastes, metals and not for other companies

Together with Società Italferro S.r.l. – Ecofer Division (part of Fiori Group, located in Santa Palomba province of Rome) and other primary operators in this sector, Italmetalli constituted an association called A.I.R.A (Associazione Industriale Riciclatori Auto) that promotes the importance of shredders in the treatment and recovery of vehicles. In addition, the association encourages respect for the environment, by also promoting the high value of scraps and its commitment to working with the institution to make efficient and right sector legislation.

Moreover, the company is part of Assofermet, a national association where commercial enterprises belong, with the distribution and pre-processing of steel products, non-ferrous metal traders, ferrous scrap dealers and hardware distribution companies.

It is associated with the B.I.R. - Bureau of International Recycling, a global association of the recycling industry which represents more than 700 companies in the private sector and 40 national trade federations from 70 countries. It is also associated with Confindustria (2).

4 LCA methodology (or environmental assessment)

Life Cycle Assessment (LCA) is an international standardized methodology that helps quantify the potential environmental impacts of goods and services (products), environmental benefits and the achievement of considering the full life cycle of the product (1).
LCA is a tool used in life cycle thinking (LCT) that is defined as the way of thinking that includes the economic, environmental, and social consequences of a product or life's process. **Figure 4.1** is a figurative representation of life cycle thinking approach and its tools.

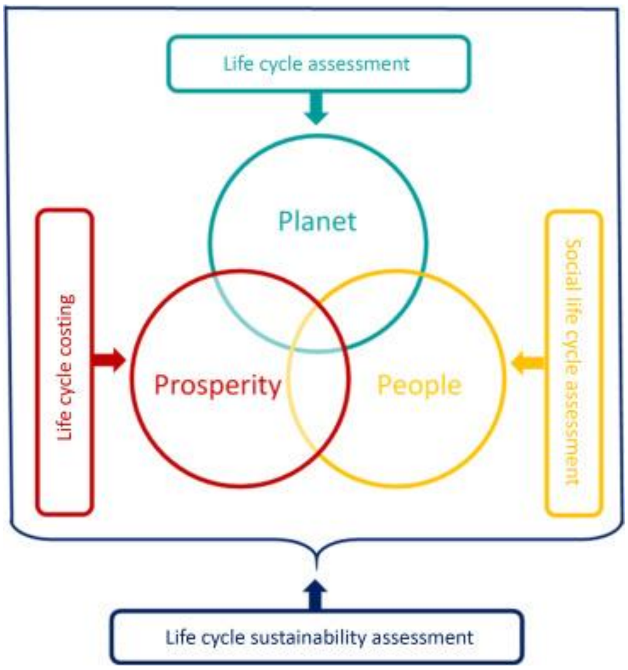


Figure 4.1 *Shows the possible link between LCT and sustainable development through the three pillars of sustainability and the multidimensionality of LCT. Adapted from "Life Cycle Sustainability Assessment for Decision-Making", Anna Mazzi, 2020.*

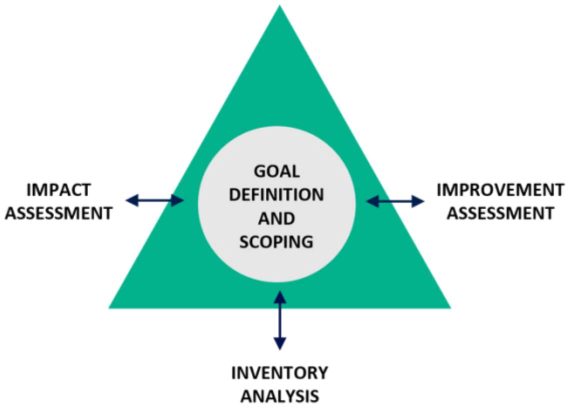
The life cycle stages of a life cycle assessment include all the raw materials, resources and energy that is consumed during the manufacturing and usage in all the product's phases from the beginning to all the end-of-life scenarios. At the same time, also transportation is included in every step. However, the system boundary should include all the life cycle stages of a product. It can be distinguished as cradle-to-gate, cradle-to-grave, gate-to-gate, or gate-to-grave analysis. The wholesome can also be called life cycle analysis. Through life cycle assessment, the conceptual framework developed from ISO 14040 to ISO 14044 can be helped in environmental management (2).

4.1 Introduction to LCA methodology and history

The new concept of exploring the life cycle of a product initially developed in the United States during the ’50-’60 with the beginning of public purchasing. One of the first mentions of the life cycle concept is by Novick (1959) (3) in a report focused on Life Cycle Analysts of cost, by RAND Corporation (an American nonprofit global policy think tank). Considering the costs was essential, including not only the purchasing cost or the use cost but of the entire system. This also covered the cost of development and the cost of end-of-life operations- The Life Cycle Analysis (not yet referred to as “assessment”) became the first tool when it comes to budget management, connecting functionality to the total cost of ownership. The life cycle approach led to general questions on methodology and standardization.

By 1985, a survey paper (Gupta & Chow, 1985) (4) described over six hundred life cycle studies, all focusing on relating system cost to functionality. From this moment the methodology problems were treated operationally, and the optimization of the system development and system performance became a core goal for the now largely applied life cycle analysis cost. Right now, we have more than half a century of experience with function-based life cycle analysis (5).

Nowadays we can speak about “modern-day LCA”, with this term we are referring to work by The Society of Environmental Toxicology and Chemistry (SETAC), that led to the general LCA framework described in the ISO 14040 series of standards. In the late 80s, questions were demanded about how to develop a methodology to assess the environmental impacts of products over their entire life cycle and SETAC had a proven approach. Here, a four-step methodology for LCA was proposed, which became the core phases of the ISO (international organization for standardization) – ISO 14040 series of LCA standards (6)



SETAC LCA framework

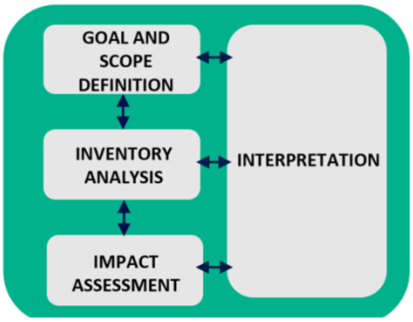


Figure 4. 2 *Four-step in SETAC and ISO 14040, taken from (6).*

4.2 ISO standards

The importance given to standards arise during the past years, they can provide clear and identifiable references recognized internationally and encourage fair competition in economies. In this sector, International Organization for Standardization (ISO) covers a wide variety of standards.

The organization which today is known as ISO began in the XX century, specifically in 1926 as the International Federation of the National Standardizing Associations (ISA). It was disbanded in 1942 with the IIWW and reorganized in ISO in 1946.

The name “ISO” acronym of “International Standard Organization” it is also mentioned to be derived from the Greek word “*isos*” meaning “*equal*”, in fact when it comes to standards the relation between two objects is that they should be equal (7).

ISO International Standards and other normative ISO deliverables (TS, PAS, IWA) are voluntary. They do not include contractual, legal, or statutory requirements. Voluntary standards do not replace national laws, with which standards users are understood to comply and which take precedence (8).

4.2.1 Environmental ISO Standards

The sentiment for environmentalism can be seen in the conservation efforts that began at the end of the 19th century. The first environmental protection law in the United States was the Refuse Act in 1899 (the Act, a section of the Rivers and Harbors Act, prohibited "dumping of refuse" into navigable waters, except by permit). However, only in the 1960s, the environment became a political and consumer issue.

In 1992, the Rio Conference on the Environment reflected increased global concerns about the environment. These concerns, coupled with the GATT negotiations in Uruguay in 1986, were the impetus behind ISO 14000.

The actual environmental standards (ISO 14000 series) deal with companies and their internal management of the environment, together with the immediate outside environment.

However, the standards also refer to the analysis of the entire life cycle of a product, from the beginning with the raw material to the all-different scenarios of the end-of-life.

These standards focus on awareness of the processes and procedures, not on a particular level of pollution, and how can they affect the environment.

Adhesion to ISO 14000 does not release a company from any regional or local regulations regarding specific issues.

Some of the standards in the ISO 14000 series are:

- ISO 14001 - Specification of Environmental Management Systems
- ISO 14004 - Guideline Standard
- ISO 14015:2022 Environmental Management – Guidelines for environmental due diligence assessment
- ISO 14020 through ISO 14021 Environmental statements and programmes for products — Principles and general requirements
- ISO 14024 - Environmental Labelling
- ISO 14031 - Environmental Performance Evaluation
- ISO 14040 through ISO 14044 - Life Cycle Assessment

- ISO 14050 - Terms and Definitions

Although the structure of ISO 14000 series is like the ISO 9000 standards (quality management system), the nature of the environmental standards creates a need for people who are technical environment professionals in addition to those required to maintain the documentation necessary for certification (7).

The normative that regulates the development of a life cycle study, and its structure is part of the 14000 series, of the 14040, more oriented on the products.
The references for the LCA are:

- ISO 14040:2006, general, reports the principle of LCA and describes its structure.
- ISO 14044:2006 is a more practical, reference for the actuation of an LCA.

In ISO 14040 there is a description of the four phases which is divided the study:

1. Definition of system boundaries, scope, and functional unit
2. Inventory analysis
3. Impact evaluation
4. Results interpretation

4.3 Structure of an LCA

The steps that regulate the execution of a life cycle assessment study will be described in the following pages. The methodology is resumed in four steps: goal and scope definition, Life cycle inventory (LCI), Life cycle impact assessment (LCIA), and Life cycle Interpretation.

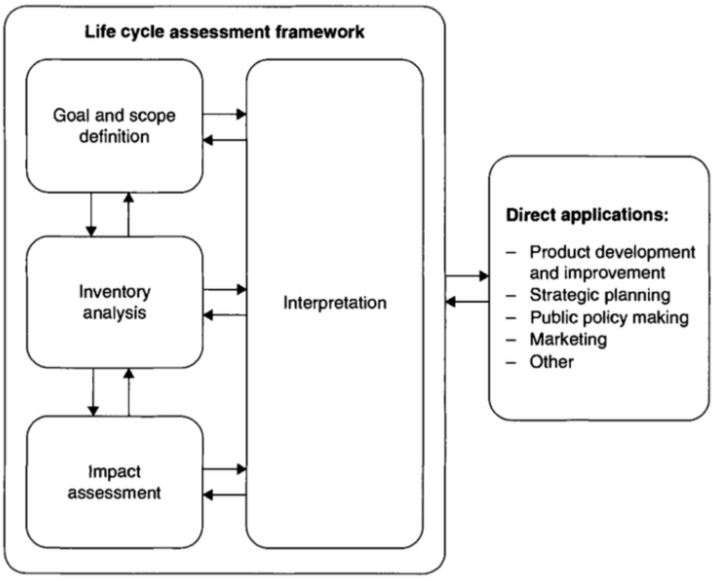


Figure 4.3 *The general methodological framework for LCA. Taken from (9).*

4.3.1 Goal and scope definition

During this first phase, the plan of the LCA study is clearly and unambiguously defined (5). The goal of the LCA should deal with the following topics:

- the intended application;
- the reasons for carrying out the study;
- the intended audience;
- the results usage (e.g., used in a comparative assertion, disclosed to the public, etc.).

The scope definition further sets the main outline on several subjects that are discussed and further refined in more detail in the later phases. These include, among others:

- system boundaries definition;
- functional unit definition;
- impact categories selection;
- treatment of uncertainty.

4.3.2 System boundaries

The system boundaries determine which process units need to be included in the LCA and which ones can be excluded. At first, the boundaries can be decided under geographical and technological criteria and can be improved later as the study progresses.

The criteria adopted need to be justified in the application by ISO 14044. Usually, the *cradle-to-grave* approach is adopted. It considers all the input and output flows, from the raw material extraction up to end-of-life (EoL).In some cases, it is not interesting to investigate the EoL stage (e.g., the case in which the innovation is concentrated on the upstream and core phases or the aim of the study is an intermediate product used in different fields) and the analysis can be stopped at the industrial gate (*cradle-to-gate* perspective).

In all cases, boundaries should be established spatially and temporally:

- Spatial boundary: also called geographic boundaries, they can influence factors such as raw material sourcing, electricity grids, the technology used and transportation.
- Temporal boundary: period over which the system is analyzed, from 1 second (e.g., combustion process) to 1000 years (landfills). Commonly, temporal boundaries are 1 h, 1 day, or 1 year (5).

4.3.3 Functional Unit

The functional unit (FU) is one of the key elements of the LCA study. It is the quantitative measure of the system/product/service function. FU is necessary to normalize all the input/output flows from LCI and express LCIA results per FU (base for communication and comparison). In the case of waste management, the amount of treated waste by the system is the representative FU.

4.3.4 Inventory analysis

With the term LCI ISO refers to the "phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle."
Here, as opposed to the first phase, is important the introduction of numbers and data, in terms of calculations, are the central concerns in inventory analysis.
The quality of data should pursue the following requirements because the results are good only if the accuracy of the input data is years (temporal limit), geographical area of the data, technology, precision, reproducibility, source, and uncertainty (models and assumptions).
All the inventories will have variability, uncertainties, and differences between data, the important is that all these problems will be considered for the resolution of the studied system. Checking the data from different sources is essential to control their quality of them. Some analyses are based on data that are not of public concern, and it makes it difficult to process an LCA in a small time. It is necessary to define two systems: foreground and background. The first one is a series of processes that define the functional unit and the second one is the system that shows the background with material and energy used.
From this, there are two different categories of data:

- primary data, specifically that describes the system and how to model it. It is where the functional unit is defined;
- secondary data, generic for materials, energy, transport, and waste treatment. They can be found in literature or database.

The basis of LCI is the unit process. A unit process is *"the smallest element considered in the life cycle inventory analysis for which input and output data are quantified"* (e.g., steel production, coal mining, recycling of wastepaper). All the processes are defined in quantitative terms with inputs and outputs. In **Figure 4.5** is possible to see the representation of a unit process, treated as a black box that converts inputs into outputs.

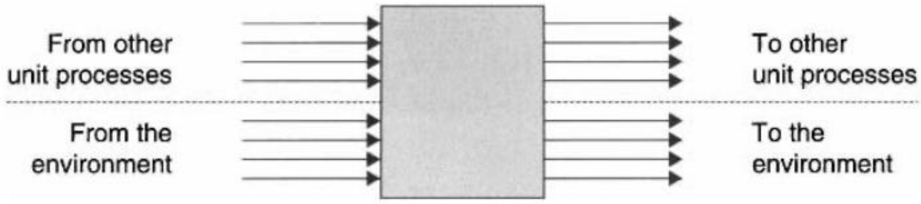


Figure 4.4 *General template of a unit process, taken from (5).*

Unit processes are the building blocks of an LCA. These processes assume a central position in LCA because products are not the only ones harmful to the environment, also the processes used are. With these pieces of information, it is possible to create a flow diagram that is a graphical representation of the whole system comprised of connected unit processes.
The figure below is a simple drawing of an example of a flow diagram with the system boundary around the processes.

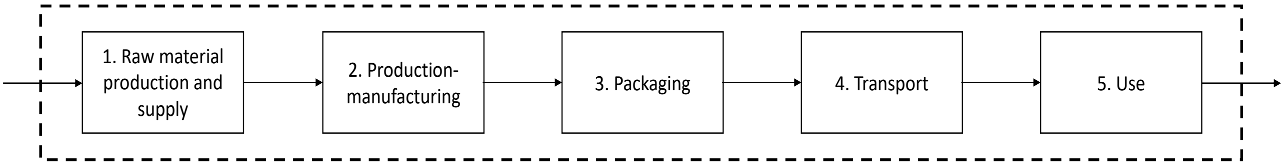


Figure 4.5 *Flow diagram of a system.*

As we can see, some unit processes are connected in simple upstream-downstream connections. But there could be also more complicated connections, flow diagrams are huge webs of unit processes. Here come the first issues, in fact for some products, upstream production processes or downstream disposal processes may be difficult to quantify and for others, the balance equations become impossible since these processes produce not just one product but several co-products.

The first one can be solved by an action called *cut-off* and the second with an *allocation*.

The *cut-off* is a method where certain input processes will be "cut-off" from the system because they are unimportant to the study. Although something is useful, there is no need to specify how these inputs are produced. It turns difficult to estimate how much an error is when a *cut-off* is made.

On the other hand, *allocation* is the "partitioning" of environmental and energy burdens when more than one product is generated from the same process. Following ISO 14040, they can be based on mass, the economic value of the product or other.

After subsequent cut-off and allocation steps, the final inventory can be processed. Graphically LCI is a table with the quantified inputs and outputs, for each of the systems considered, expressed with the functional unit (5).

4.3.5 Impact assessment

"Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product" (9).

Life cycle impact assessment is a quantitative and qualitative evaluation of the potential environmental impacts of the product/system/process under study based on the data from LCI. LCIA translates data from materials and energy consumption into impact indicators and then, categories. There are several steps in an impact assessment, they are shown in **figure 4.7** and are concluded through a series of steps recommended by ISO 14040 and ISO 14044 (10).

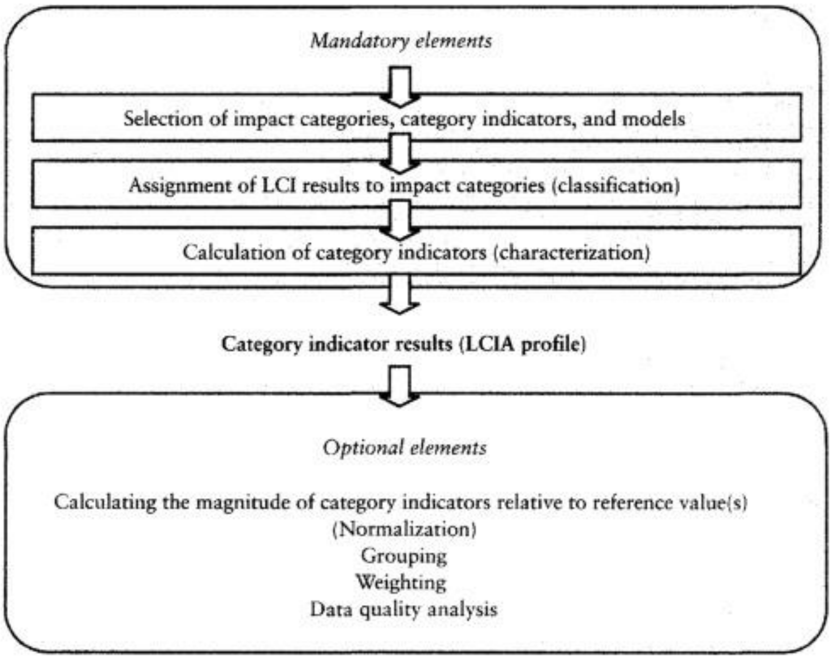


Figure 4.6 *Elements of life cycle impact assessment. Taken from (10).*

A model can be developed, once the indicator is defined, that can predict the value as a function of an emission. The indicator value is obtained by multiplying the emission by a characterization factor. The sum of indicators is the category indicator result.

The category indicator results can be analyzed by normalization, grouping and weighting (10).

One of the methods used for the evaluation of the impact is the ReCiPe2016. This method is analyzed in detail in **chapter 5.3**.

4.3.6 Interpretation and evaluation

Interpretation is the last big phase of the life cycle assessment. ISO 14044 defines it as the *"phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated about the defined goal and scope to reach conclusions and recommendations."*
ISO mentioned several items to consider about the interpretation to arrive at conclusions:

- relevance of the definitions of the system functions, the functional unit, and the system boundary;
- identification of significant issues (contribution analysis);
- an evaluation of the study’s completeness, including sensitivity and consistency checks;
- limitations identified by the data quality assessment and the sensitivity analysis;
- conclusions and recommendations.

ISO does not suggest any specific procedure or technique be adopted during interpretation; it is mentioned to carry out an uncertainty analysis (5).

There can be a distinction between procedural and numerical approaches (11):

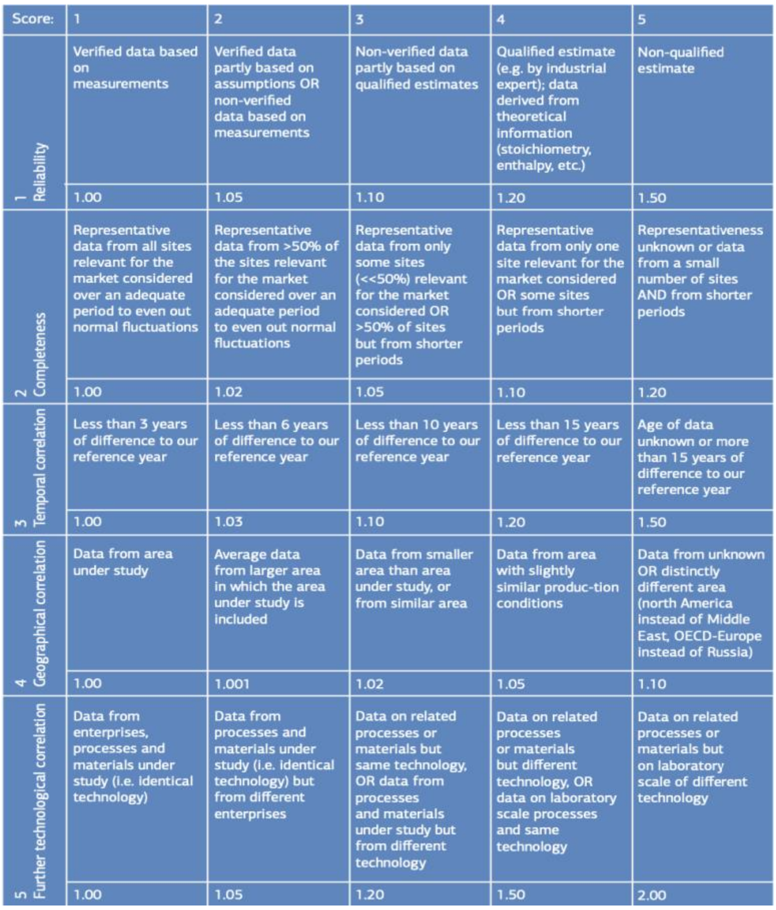
- Procedural approaches include all types of analyses that deal with the data and results concerning other sources of information.
- Numerical approaches include those approaches that somehow deal with the data that is used during the calculations.

This distinction helps to understand better the interpretation. In one way it is a comparison between data and results. On the other side, it is close to a systematic analysis with the help of analytic techniques. Some software already contains programs to run Monte Carlo analysis (sensitivity) and others.

The final evaluation of data and processes consists of qualitative control. For example, to think about possible neglected variables, apply a qualitative or quantitative systematic analysis of input data changes implications or discuss variations on the goal and scope from the beginning of the study.

4.3.6.1 Uncertainty analysis

Data, even though the quality needs to be accurate and truthful, are never completely accurate and uncertainties associated are defined. The quality of the data may be related to several data quality indicators, which specify the quality related to the use in the study. The following data quality indicators describe the area of interest and attach a number between 1 and 5 in each category per single data. In the table below it is possible to see the indicators (12).



Score:	1	2	3	4	5
1 Reliability	Verified data based on measurements	Verified data partly based on assumptions OR non-verified data based on measurements	Non-verified data partly based on qualified estimates	Qualified estimate (e.g. by industrial expert); data derived from theoretical information (stoichiometry, enthalpy, etc.)	Non-qualified estimate
	1.00	1.05	1.10	1.20	1.50
2 Completeness	Representative data from all sites relevant for the market considered over an adequate period to even out normal fluctuations	Representative data from >50% of the sites relevant for the market considered over an adequate period to even out normal fluctuations	Representative data from only some sites (<<50%) relevant for the market considered OR >50% of sites but from shorter periods	Representative data from only one site relevant for the market considered OR some sites but from shorter periods	Representativeness unknown or data from a small number of sites AND from shorter periods
	1.00	1.02	1.05	1.10	1.20
3 Temporal correlation	Less than 3 years of difference to our reference year	Less than 6 years of difference to our reference year	Less than 10 years of difference to our reference year	Less than 15 years of difference to our reference year	Age of data unknown or more than 15 years of difference to our reference year
	1.00	1.03	1.10	1.20	1.50
4 Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from smaller area than area under study, or from similar area	Data from area with slightly similar produc-tion conditions	Data from unknown OR distinctly different area (north America instead of Middle East, OECD-Europe instead of Russia)
	1.00	1.001	1.02	1.05	1.10
5 Further technological correlation	Data from enterprises, processes and materials under study (i.e. identical technology)	Data from processes and materials under study (i.e. identical technology) but from different enterprises	Data on related processes or materials but same technology, OR data from processes and materials under study but from different technology	Data on related processes or materials but different technology, OR data on laboratory scale processes and same technology	Data on related processes or materials but on laboratory scale of different technology
	1.00	1.05	1.20	1.50	2.00

Table 4.1 *Pedigree matrix. Taken from (13).*

1. Reliability

It relates to the resources, acquisition and verification procedure used to obtain the data. This indicator is independent of the data quality goal.

2. Completeness

It relates to the statistical properties of the data on how representative the sample, does the sample include an adequate amount of data. As the reliability, it is independent of the data quality goal.

3. Temporal correlation

It represents the temporal correlation between the starting year of study and the year when the data were obtained.

4. Geographical correlation

It illustrates the geographical correlation between the defined area of the study and the final obtained data.

5. Further technological correlation

It concerned all other aspects that temporal and geographical do not consider.

A common method used to evaluate uncertainties is the Monte Carlo Simulation.
To perform a Monte Carlo simulation there is the need to specify the parameters as uncertainties distributions. The method varies the parameters at random, but each parameter has an uncertainty distribution. The repetition of calculation (in an output equation) produces a distribution of the predicted output values. This method reveals the uncertainty distribution of a parameter into several non-overlapping intervals, each having equal probability. Moreover, from each interval, a value is selected randomly according to the probability, leading to more precise samples. One of the first to discuss Monte Carlo simulation was Huijbregts, 1998 (14). This is a statistical method that consists in generating and propagating uncertainties to the system variables. Using a reasonable number of simulations (e.g., 1000-10000), a result can be described as a probability distribution characterized by average values and standard deviations. This simulation consists in replicating evaluations changing parameters inside the confidence interval (the higher the interval, the higher the data uncertainties).
To apply the Monte Carlo approach, there is the need to translate information into a standard distribution type. In SimaPro (**chapter 5**) there are 4 different distributions: range, triangular, normal, and lognormal. The type used in this thesis is lognormal, which needs standard deviation and best guess value. It is the most important distribution in LCA and occurs when values with a normal distribution are multiplied. The 95% confidence interval is defined by dividing or multiplying the best guess value with the squared geometric standard deviation. The square is often written as σ^2 (13).
In addition to the uncertainty analysis, there is the sensitivity that consists of the possibility to modify assumptions and recalculate the results to assess the robustness of the model created. The scope of the sensitivity analysis is to evaluate uncertainties

caused by exclusion criteria, allocation choices, data quality and choices of impact categories in an LCA study.

4.3.7 Conclusion

This final part aims to give transparency to the study by defining the limitation and recommendation for future improvements.

5 Software, Database, and Methods

Life Cycle Assessment evaluates the environmental impacts of the life cycle of products. In the past year software, database, and methods were studied and developed to help study LCA.

5.1 SimaPro

The LCA analysis that is discussed in this Thesis was made using SimaPro software (v. Ph.D. 9.4.0.2) developed by PRé Sustainability B.V.

Everything started in 1990 when it began to wonder "how can we measure eco?" (1). That is when SimaPro was developed. Today, many leading companies, researchers, and consultants are used to adopting SimaPro for their work.

The software can be used for supporting sustainability reports, carbon and water footprint analysis, product design, generating environmental product declarations, and determining key performance indicators. The validity of this software is due to the conformity of the international ISO normative 14040 and 14044 (11):

- **UNI EN ISO 14040** Environmental management, Life Cycle Evaluation, Principles, and frameworks (9)

- **UNI EN ISO 14044** Life Cycle Evaluation, Requirements, and guidelines **Error! Reference source not found.**(5)

5.1.1 SimaPro structure

With SimaPro it is possible to model and analyse complex life cycles systematically and transparently. Measure the potential environmental impacts of products and services across all life cycle stages. Identify the hotspots in every link of the supply chain, from the extraction of raw materials to manufacturing, distribution, use, and disposal.

Inside the software a division has been made between the process and product stages (6):

- Processes are "packages" that contain different kinds of information, from the environmental ones to the social and economic about in and outflows, such as raw materials utilized, emissions, and avoided impact.
  Each pack comes with its documentation (author, technical characteristics, data source, etc.) and it is necessary for the modulation of the studied system.
  They are classified as *unit processes* (elementary flows are collected in processes) or *system processes* (simply a list of elementary flows without more details), they interact with each other with connectors as trees or networks.

  Product stages are utilized to describe the "different phases" of the life cycle, such as:

1. Assembly: includes all the data about raw materials, energetic inputs, and transport (not just of raw materials but also products).
2. Life cycle: it describes the usage phase.
3. End of life: contains all the possible ways in which a product can end its life with flows and environmental impacts.
4. Disassembly: it describes the product’s parts with impacts, and it defines the final waste treatment.
5. Reuse: environmental impacts, avoided and none, connected to the reutilization of the product.

5.2 Ecoinvent

Ecoinvent is one of the data banks presented in SimaPro software and it is the one that has been utilized in this Thesis project (ecoinvent v3.7.1).

The data collection for the creation of one of the first storages, utilized in the inventory part of the LCA study, is from the early ’90, created from the initiative of different organizations and institutes in Switzerland. However, the data from different banks that refer to the same material or process did not match.

Accordingly, the results of an LCA study depend on the institute that has utilized its database during the LCI phase, thus resulting in inconsistency and incomplete. Furthermore, the updating of the data bank, necessary to maintain a good quality of the study, was an effort for the single institute that was working on it.

In 1998, after the direction and support of the Swiss Centre for Life Cycle Inventories (founded in 1997), the idea of unifying all databases took hold. In 2003 the first version of Ecoinvent was released, and in 2007 a new updated version came out, thanks to all the European organizations (7).

The amount of data arrived at ecoinvent, gave it the chance to be the reference for other environmental certification instruments like Design for Environment (DfE), Integrated Product Policy (IPP) (8), or Environmental Product Declarations (EPD) (9). Inside, the data are divided into macro areas: chemical products, energy, transport, etc; then split up into micro categories: inorganic and organic chemicals, etc.

5.3 ReCiPe method

LCA evaluate the environmental impacts of the total life cycle of products, from the raw material used to the end-of-life, phase called Life Cycle Impact Assessment (LCIA). Within the LCIA emissions and resource consumption within the inventory are converted into a limited number of environmental impact categories. This is done by so-called characterization factors, that indicate the environmental impact per unit stressor (10).

Goedkoop et al. (2009) developed an LCIA method called ReCiPe 2008 that presents harmonized characterization factors at *midpoint* and *endpoint* levels. The two approaches are complementary. The method addresses several environmental concerns at the midpoint level (problem-oriented). On the other hand, at the endpoint level (damage-oriented), characterization factors correspond to three areas of protection: human health, ecosystem quality and resource scarcity (10).

The general structure of an LCIA is composed of elements like classification and characterization, which can convert the results from the inventory phase into indicators, and from other optional elements as normalization and weighting.

- Classification

In this phase, inventory data are organized, and all solid, liquid, and gaseous emissions are assigned to a category impact.

Using a problem-oriented *methodology* it is possible to divide the methods to values two impact categories:

1) Midpoint-oriented in case the data are converted into intermedium level impact category.
2) Endpoint-oriented in case damage indicators are utilized (not common to all methods).

- Characterization

This method can determine the quantitative single emission. Through equivalent factors, we can compare how a substance contributes to a certain impact category, compared to a reference one.

- Normalization

The data obtained can be normalized and, processed to obtain values for evaluating the entire system. This phase reveals how big the impact of single categories is on the whole environmental problem.

- Weighting

In this phase, a weight is applied to each environmental impact category. Based not on scientific consideration but on social, political, and economic bases. The scope is to establish the importance of one category considering the others and summing up the result to have a unique indicator. For this method usually, there are different approaches:

1. Monetization, damages expressed in monetary terms (cost to avoid an environmental problem, etc)
2. Goal distance, regarding the national and international laws.
3. Expert evaluation, a group of experts will judge the category impact and give the weight.

5.3.1 ReCiPe 2016

The study will be realized following the ReCiPe 2016 method, an updated version of ReCiPe 2008, the impact categories considered are the following present in **Figure 5.1**.

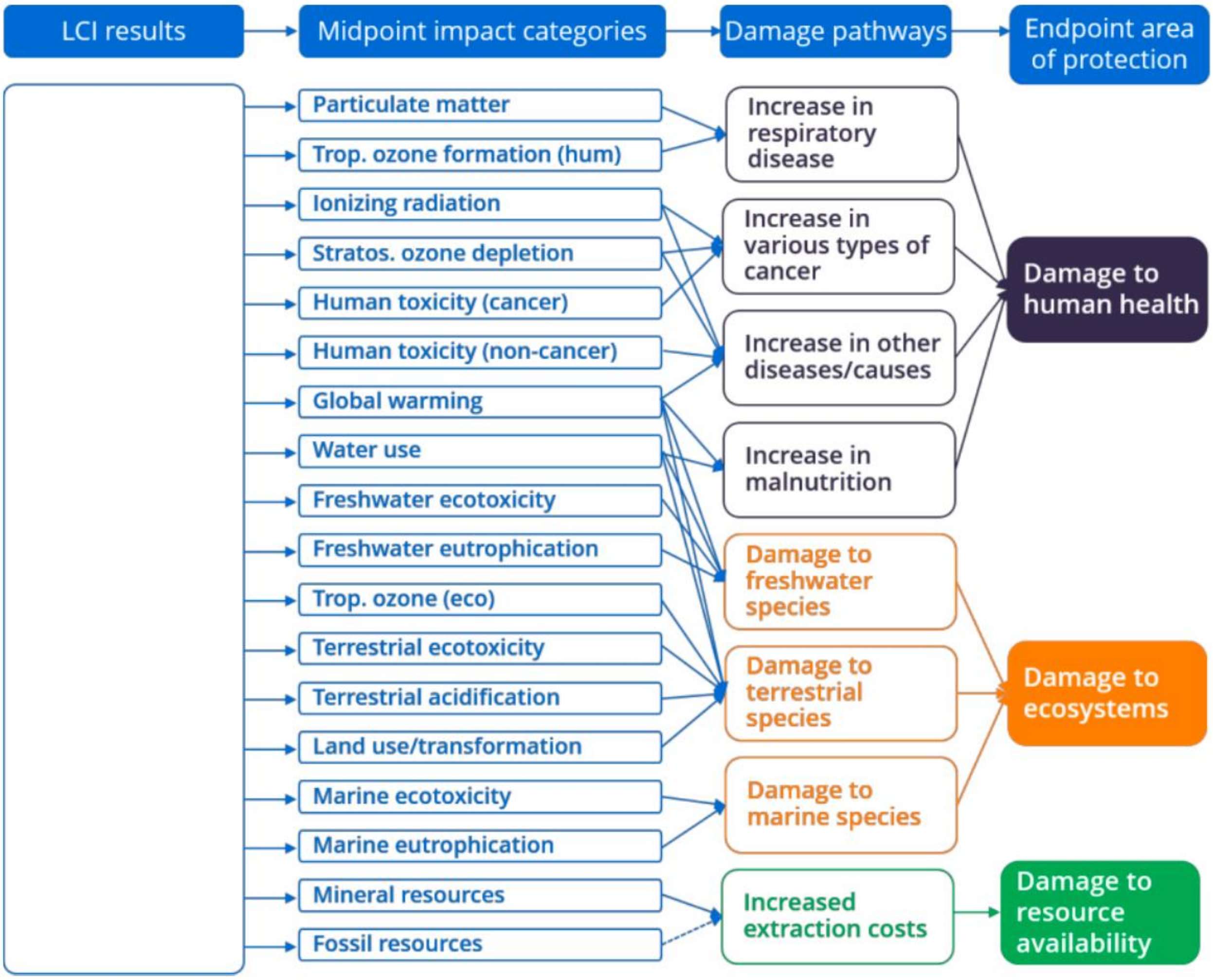
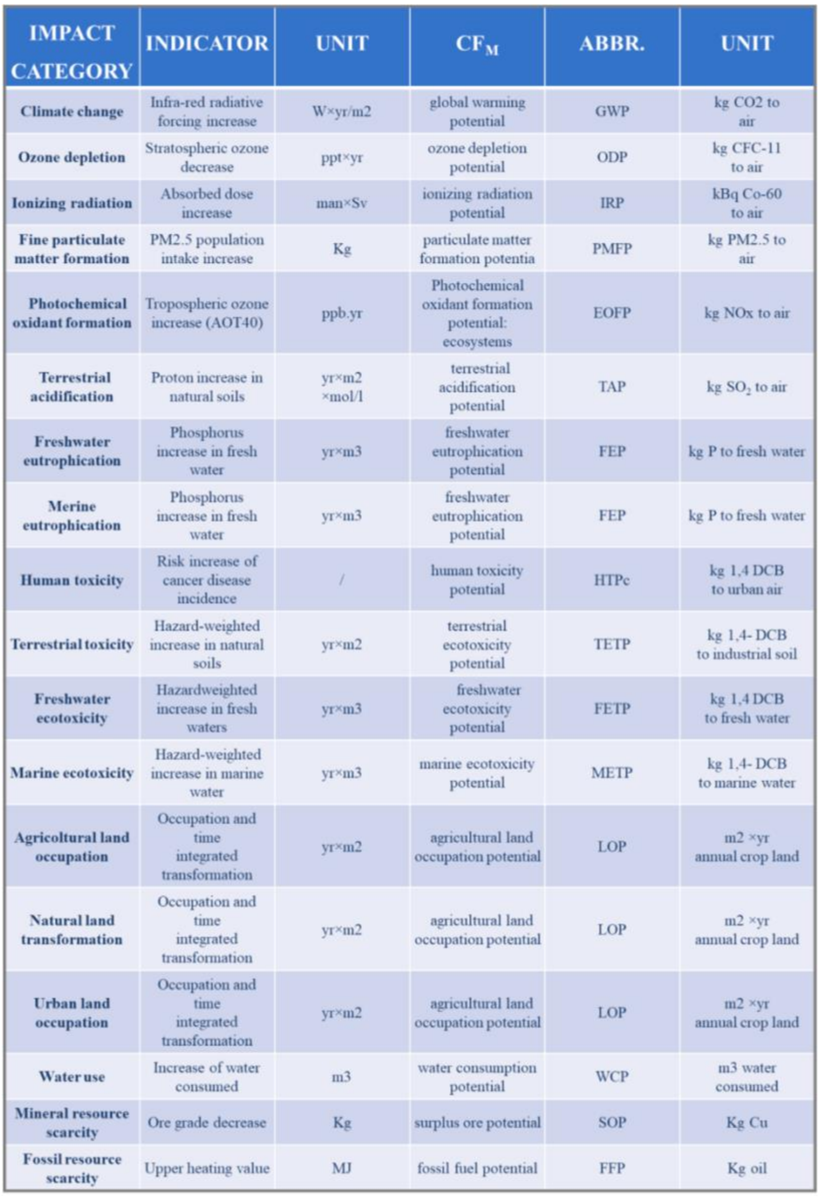


Figure 5.1 *Overview of the impact categories that are covered in the ReCiPe 2016 method and their relation to the areas of protection. The dotted line means there is no constant mid-to-endpoint factor for fossil resources. Taken from (11).*

Impact categories reflect issues of direct environmental relevance. For example, waste is not a category, but the effects of waste will result in climate change, land use, toxicity, etc.

Furthermore, at the midpoint, categories are defined at the place where mechanisms common to a variety of substances come into play (6).

Each impact category has an indicator, unit, and abbreviation (**Figure 5.2Error! Reference source not found.**).



IMPACT CATEGORY	INDICATOR	UNIT	CF_M	ABBR.	UNIT
Climate change	Infra-red radiative forcing increase	W×yr/m2	global warming potential	GWP	kg CO2 to air
Ozone depletion	Stratospheric ozone decrease	ppt×yr	ozone depletion potential	ODP	kg CFC-11 to air
Ionizing radiation	Absorbed dose increase	man×Sv	ionizing radiation potential	IRP	kBq Co-60 to air
Fine particulate matter formation	PM2.5 population intake increase	Kg	particulate matter formation potentia	PMFP	kg PM2.5 to air
Photochemical oxidant formation	Tropospheric ozone increase (AOT40)	ppb.yr	Photochemical oxidant formation potential: ecosystems	EOFP	kg NOx to air
Terrestrial acidification	Proton increase in natural soils	yr×m2 ×mol/l	terrestrial acidification potential	TAP	kg SO_2 to air
Freshwater eutrophication	Phosphorus increase in fresh water	yr×m3	freshwater eutrophication potential	FEP	kg P to fresh water
Merine eutrophication	Phosphorus increase in fresh water	yr×m3	freshwater eutrophication potential	FEP	kg P to fresh water
Human toxicity	Risk increase of cancer disease incidence	/	human toxicity potential	HTPc	kg 1,4 DCB to urban air
Terrestrial toxicity	Hazard-weighted increase in natural soils	yr×m2	terrestrial ecotoxicity potential	TETP	kg 1,4- DCB to industrial soil
Freshwater ecotoxicity	Hazardweighted increase in fresh waters	yr×m3	freshwater ecotoxicity potential	FETP	kg 1,4 DCB to fresh water
Marine ecotoxicity	Hazard-weighted increase in marine water	yr×m3	marine ecotoxicity potential	METP	kg 1,4- DCB to marine water
Agricoltural land occupation	Occupation and time integrated transformation	yr×m2	agricultural land occupation potential	LOP	m2 ×yr annual crop land
Natural land transformation	Occupation and time integrated transformation	yr×m2	agricultural land occupation potential	LOP	m2 ×yr annual crop land
Urban land occupation	Occupation and time integrated transformation	yr×m2	agricultural land occupation potential	LOP	m2 ×yr annual crop land
Water use	Increase of water consumed	m3	water consumption potential	WCP	m3 water consumed
Mineral resource scarcity	Ore grade decrease	Kg	surplus ore potential	SOP	Kg Cu
Fossil resource scarcity	Upper heating value	MJ	fossil fuel potential	FFP	Kg oil

***Figure 5.2** Summary of midpoint categories, related impact indicators and characterization factors. Taken from (2).*

The transformation between midpoint impact categories and endpoint impact categories is made by multiplying the midpoint categories by a conversion factor (Equation 1). So, endpoint characterization factors (CF_e) are derived from the CF_m with a constant.

$$CFe_{x,c,a} = CFm_{x,c} \times F_{M\rightarrow,E,c,a}$$

Equation 1

CF_m: endpoint impact category
CF_e: midpoint impact category
F_m: conversion factor from midpoint to endpoint

Whereby “*c*” stands for the cultural perspective, “*a*” implies the area of protection (human health, terrestrial ecosystems, freshwater ecosystems, marine ecosystems, or resource scarcity), “*x*” is the stressor of concern and $F_{M\rightarrow,E,c,a}$ is the midpoint to the endpoint conversion factor. Because all the environmental mechanism

These midpoint-to-endpoint factors are constant per impact category because environmental mechanisms are identical for all stressors after the midpoint impact location on the cause-effect pathway. For all types of impact categories there are constant global midpoint to endpoint factors, the only exception is for fossil resource scarcity, due to a lack of understanding of the cause-effect pathway (6). The characterization factor's purpose is to make comparable different values, giving the same measurement unit.

The ReCiPe 2016 method provides impact categories (**Error! Reference source not found.**), they are converted into 3 macro categories: human health (HH); ecosystem diversity (ED) and resource availability (RA).

- Human Health (HH) (6)

Human Health damages are usually identified in terms of *Disability-Adjusted Life Years* (DALY). In LCA the concept of DALY was introduced by Hofstetter in 1998, his studies were based on a work for the world health organization. DALY is derived from human health statistics, and it is represented by the sum of life years lost (YLL) and the one lived in disability conditions (YLD). No variations for the future generation are considered and, independently of age, the same value per year of life is attributed.

$$\mathrm{DALY} = \mathrm{YLL} + \mathrm{YLD}$$

Equation 2

$$\mathrm{YLD} = \mathrm{w} * \mathrm{D}$$

Equation 3

- ➔ W: a factor that depends on the importance of the diseases (from 0, complete health, to 1, death).
- ➔ D: duration of the disease, disability.

DALY depends also on subjective factors and must refer to a time and place interval, considering that using global averages can cause important uncertainties.

- Ecosystem diversity (ED) (6)

Nowadays the importance given to the ecosystem it is not something new, specifically, this relevance is due to the biodiversity, the aesthetic and cultural value, the ecology, and genetic information that is used; therefore, is fundamental to build a parameter thorough which count the damages that the life cycle of the product generate into the environment.
To describe the quality of the ecosystem it is possible to use material and energy flow. The quality of the ecosystem can be described with the absence of anthropogenic activities. The level of disturbance is what determines the quality of the ecosystem.
In ReCiPe 2016 the focus is on the fluxes at the species level, as a result, this diversity represents the quality of the ecosystems.

Since anthropogenic factors may affect all species groups, it is impossible to monitor them all. It is essential to choose those groups that can be used as appropriate representatives of the quality. It is important to choose between:

- Complete and irreversible extinction of species.
- Reversible or irreversible passing of a species or the stress on a species, for a given region, at a certain time.

Because of that, to determine the quality of the ecosystem it is used the Potential Disappear Fraction of species (PDF), the fraction of disappeared species in a certain time range and certain region. The importance given to aquatic or terrestrial species is the same.
The endpoint damage characterization factor (CF_{ED}) is calculated with the sum of PDF, multiply by the specie's density (SD) as in the following equation:

$$CF_{ED} = PDF_{terr} * SD_{terr} + PDF_{fw} * SD_{fw} + PDF_{mw} * SD_{mw}$$

Equation 4

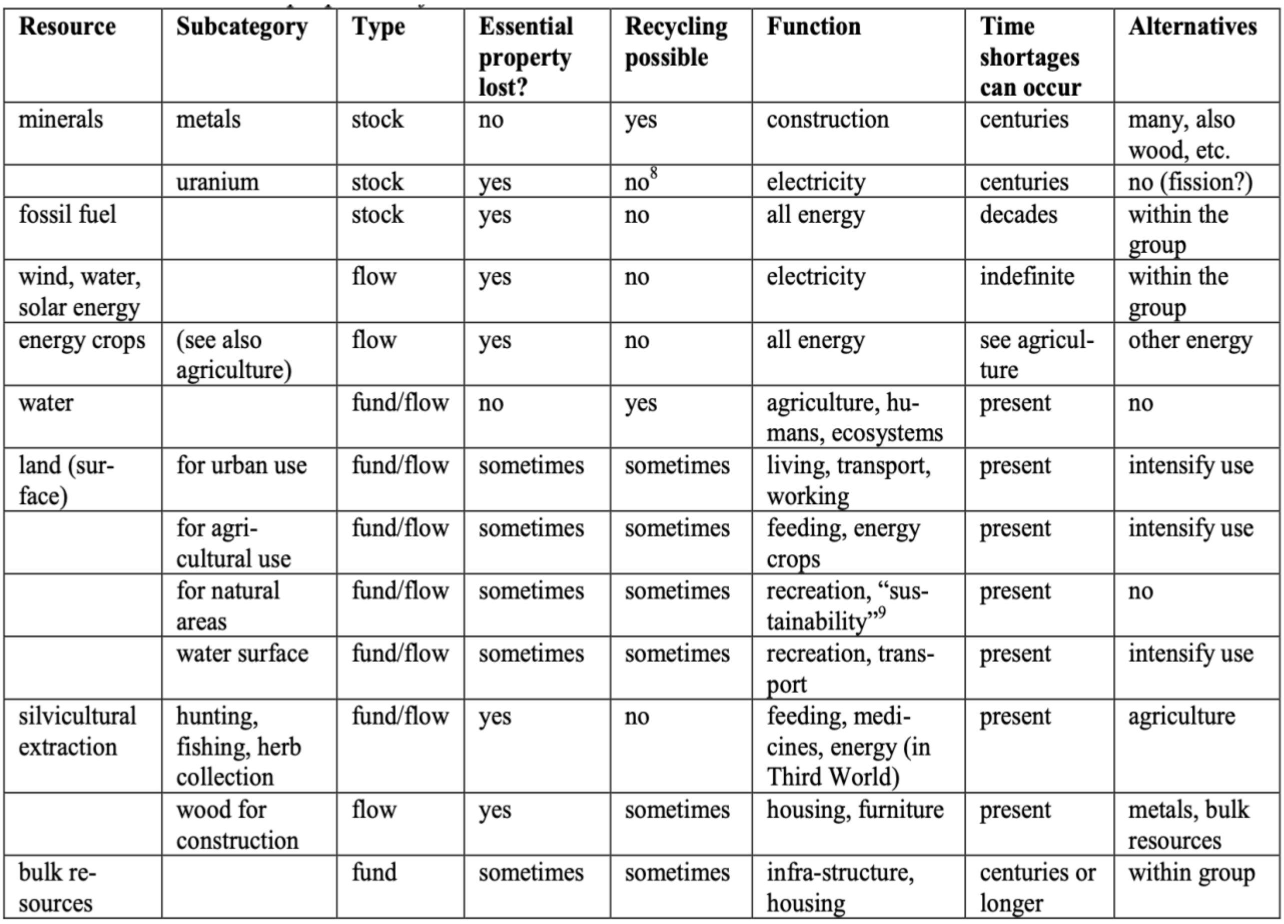
- ➔ Terr: terrestrial systems,
- ➔ Fw: freshwater systems,
- ➔ Mw: marine water systems.

It is necessary to know:

- The total number of species on earth
- The distribution
- The total area of the earth and the volume of freshwater and marine

- Resources availability (RA) (6)

For mankind, it is "real" the risk of running out of resources for future generations, and it is often quoted as an important problem. Moreover, it is important to distinguish between a material and the function it can provide, to better understand the resource needs.
The table below provides an overview of functions and properties that some types of resources give.



Resource	Subcategory	Type	Essential property lost?	Recycling possible	Function	Time shortages can occur	Alternatives
minerals	metals	stock	no	yes	construction	centuries	many, also wood, etc.
	uranium	stock	yes	no[8]	electricity	centuries	no (fission?)
fossil fuel		stock	yes	no	all energy	decades	within the group
wind, water, solar energy		flow	yes	no	electricity	indefinite	within the group
energy crops	(see also agriculture)	flow	yes	no	all energy	see agriculture	other energy
water		fund/flow	no	yes	agriculture, humans, ecosystems	present	no
land (surface)	for urban use	fund/flow	sometimes	sometimes	living, transport, working	present	intensify use
	for agricultural use	fund/flow	sometimes	sometimes	feeding, energy crops	present	intensify use
	for natural areas	fund/flow	sometimes	sometimes	recreation, "sustainability"[9]	present	no
	water surface	fund/flow	sometimes	sometimes	recreation, transport	present	intensify use
silvicultural extraction	hunting, fishing, herb collection	fund/flow	yes	no	feeding, medicines, energy (in Third World)	present	agriculture
	wood for construction	flow	yes	sometimes	housing, furniture	present	metals, bulk resources
bulk resources		fund	sometimes	sometimes	infra-structure, housing	centuries or longer	within group

Table 5.1 *Functions and properties of resources. Taken from (6).*

The ReCiPe method is based on the geological distribution of resources (mineral and fossil) and explains how resource usage can change the future extraction and procurement of themselves. The model is based on the *Marginal Cost Increment* due to the extraction.

This function is expressed in $/kg^2. It is the cost increment of a product (∆Cost in $/kg) due to extraction/extraction rates (kg) of the resource "r". The cost increase in $/kg must be multiplied by the consumed amount obtaining a value in $.

5.4 Cultural Theory

The ReCiPe method adopts the concept of "*cultural theory*", which is a theory developed by studying the behaviour of people.

Within LCA, cultural theory has been used to define different scenarios. The first attempt was developed by the anthropologist Mary Douglas, and it was originally associated with a social anthropology approach, based on the structure, and functioning of groups within societies. This theory helps identify and compare different ways of life, it assumes that society can be characterized along two axes - *group* and *grid*. The *group* represents the extent an individual is incorporated into a group. On the other side, the *grid* describes the degree to which an individual's life is decided by externally imposed structures. Each combination results in 5 archetypes of people: the individualist, the hierarchist, the egalitarian, and the fatalist. Each of them follows a composition of ideologies, cultural biases, social relationships, moral beliefs, concerns, or interests (12).

Later, the theory has been extended by other researchers, they amplified the different archetypes. For example, one of the latest research projects by Michael Thompson et al. 1990 (14) was about considering the dilemma between benefit and risk, global and local and incorporating it into the archetypes. **Figure 5.3** gives a graphical representation of different approaches.

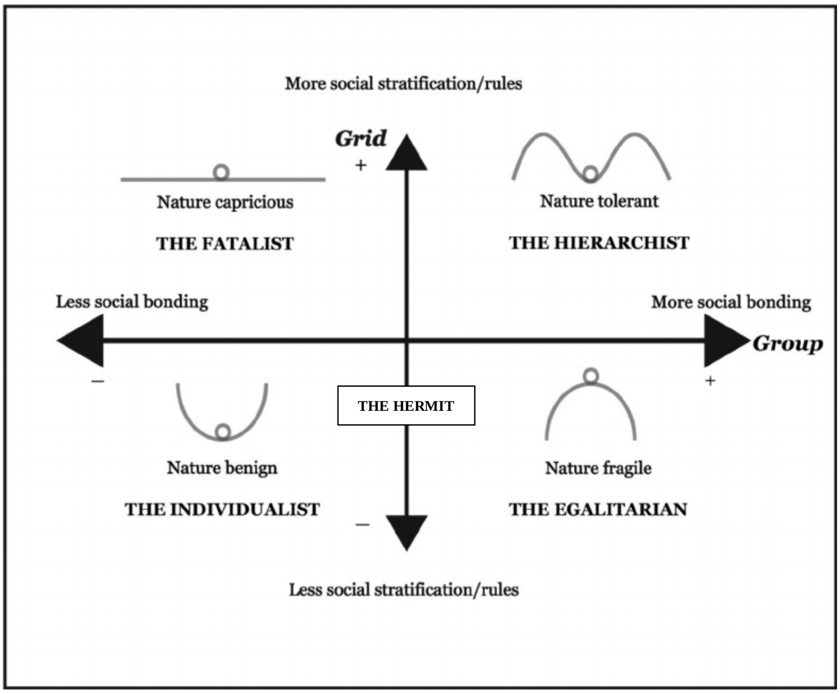


Figure 5.3 *The Four Worldviews and Views of Nature described in the Cultural Theory of Risk. Adapted from (13).*

The individualist view is of weak social bonds and minimal social structure, all about ambition and personal freedom. Here nature is benign and will adjust human actions. The fatalist is also for weak social bonds, and a stratified society governed by rules, nature is unpredictable. Keywords for fatalists are comfort and pleasure. Then the hierarchy perspective is about strong social bonds that are vertical and governed by numerous rules. Nature can accommodate human actions to a point which can be planned by scientific experts. The egalitarian worldview is strong in social bonds between people who only agreed-upon rules and a philosophy of collectivity (13).

The egalitarian worldview is of strong social bonds between people with only internally agreed-upon rules and a general philosophy of collectivity. The corresponding myth of nature is that nature is fragile and in a precarious balance with society (the ball can be easily tipped to roll down the hill) (Thompson et al., 1990 (14)).

6 Life Cycle Analysis

The presented study uses the LCA methodology to evaluate and compare different treatment scenarios of hazardous waste. For this reason, the second part of the work, the experimental part, will be divided into the different phases of the technologies that were explained in the previous chapters. This section will be divided into goal and scope definition, life cycle inventory, impact evaluation and result interpretation. The use of SimaPro software is described in the last part.

6.1 Goal and scope definition

The goal and scope of this study are to evaluate an innovative scenario of end-of-life (EoL) treatment of hazardous waste derived from the metal recycling industry Italmetalli.

In this study, the evaluation of the process is particularly interesting for the addition of a leaching process that will induce metal recovery and reduce the danger of the product.

The research, with the collaboration of Italmetalli, is a good comparison with a more traditional scenario, and it is useful to research since it is a better comprehension of the environmental impact of waste treatment.

As explained in **chapter 2**, EoL treatment, which could be incineration or landfill, has a strict correlation with the 17 Sustainable Development Goal 2030 Agenda (1), for this reason, is important to do continuous research about this theme.

To clarify the importance of this study, it was conducted for an internal audience (Italmetalli) as an R&D project, and to be applied and used, for example, to update the EMAS (2) of the group in the future. Italmetalli released the last version of its environmental declaration last year (3).

6.2 System Boundaries

The system is designed as an end-of-life treatment because the working process is not from the starting (extraction of raw material – cradle) to grave (EoL) but the work is done on the waste itself, so the treatment and final management.

This process is born as the disposal of hazardous waste, not considering any transportation if not the one to bring some reagents that come from outside the company.

Figure 6.1 is shown the schematic representation of the system boundaries of the innovative scenario described in this study. Below is the legend for the scheme.

The system boundary underlined in black shows where the Italmetalli work ends. Outside the boundary, signed with a dotted line, the emissions to the air.

Those emissions were not considered and not calculated inside the system and in the process (not added to the model) because as an internal decision, they were considered irrelevant being very low or absent. Their absence is due to the installation of a thermal oxidizer where the pyrogas pass and the pollutants (VOC, CO, chlorine compounds, …) are removed.

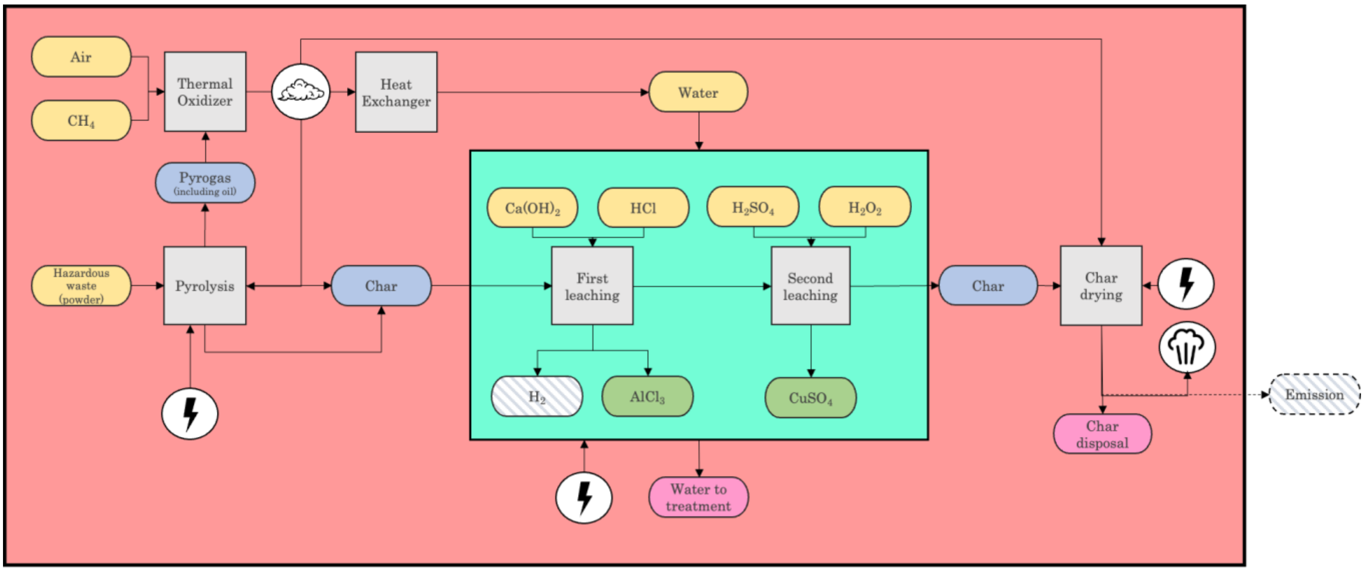


Figure 6.1 *System boundary representation of the innovative scenario.*

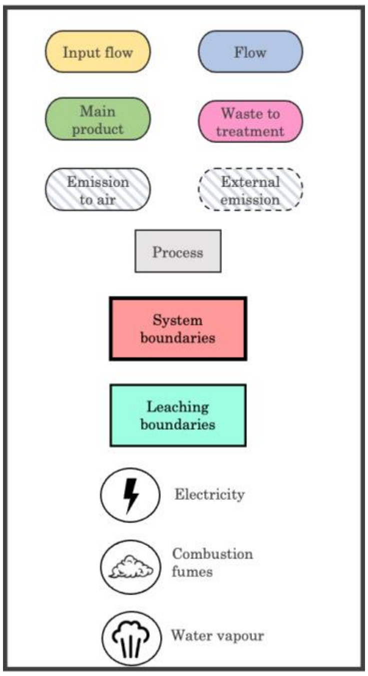


Figure 6.2 *System boundaries' legend.*

The boundaries include all the scenario that will take place inside the company and as written above it will start not with the transportation-extraction of material but with the powder (the waste) as input in the system.

The system is divided into three parts: one slow pyrolysis, one section of oxidation and thermal recovery and the metal recovery part.

The pyrolysis part is constituted by a continuous plant. The feedstock (powder, hazardous waste) and it's divided into 2 parts by a cyclone. The gaseous part, pyrogas, goes to the thermal oxidizer while the char, the solid, passes directly to the metal recovery process. To guarantee an energy recovery (thermal energy that will be used inside the plant) the thermal oxidizer is utilized. Pyrogas enter it and the oxidizer removes all the pollutants. This part both feeds with methane and air. Then the combustion fumes formed will go into another part of the system.

In the middle of the flowsheet, a light blue system differs from the rest. This process is needed as metal recovery, it is the leaching part. The primary product from the leaching, $AlCl_3$ and $CuSO_4$ are considered material recovery treatment results, while the char disposal will end in a landfill. The char produced, right now, cannot be utilized but it is under study and maybe it will find a solution (e.g., formation of concrete).

The wastewater produced after the leaching process (the precipitation part) is considered hazardous for the environment, because of the substance contained. It is under study process to elute it and uses this wastewater as a flocculant in the process.

In the following chapter, the life cycle inventory, inputs, and outputs of the system will be explained in detail.

There is no explicit emission as output in the air of VOC, NO_x, or CO because of the presence of the thermal oxidizer inside the plant.

6.3 Functional Unit Definition

The functional unit (FU), meaning the quantity of hazardous waste considered entering the system, is 1 ton.

Everything the system needs was calculated based on this FU of 1 ton. This quantity was calculated considering the waste produced per day in Italmetalli and, since the scenario is a pilot scheme based on a smaller quantity, the functional unit is the result of scale-up.

All the analyses from now on will be shown in 1 ton.

6.4 Allocation criteria

No allocation criteria have been employed since the only relevant outputs from the study are the two products and the final char.

7 Inventory analysis

After the first experimental stage, during which the parameters were studied and the system boundaries set to build the life cycle, it is time to pass to the second and most time-consuming step: the inventory analysis.

The inventory is made for the single process, the innovative scenario, and it was modelled with its mass balance in SimaPro to evaluate the potential environmental impacts.

First, an assumption about this inventory. The life cycle studied in this Thesis is the result of internal research conducted by Italmetalli. For this reason, most data presented and used in the models are considered “primary” data, considered high-quality information since collected directly onsite from experiments conducted on a lab-scale prototype. Besides this, most of the content, especially the data, is subjected to the company’s know-how and they will be referenced as “internal communication” with no external connection.

The mass balance, just considering *input=output*, was calculated over the waste per year and not per ton. For this reason, there might be some inaccuracy in the calculation, for example, the air flows for the thermal oxidizer are not considered in the yearly mass balance.

	Parameter	**ton/year**
Input	Hazardous Waste	396.0
Output	Char (sent to leaching)	251.2
	Pyrogas (sent to energy recovery)	144.8

Table 7.1 *Mass Balance ton/year.*

The data included in the inventory are complete. All the input and output that characterize the system boundaries (**chapter 6**) are explained below. The energetic consumption was calculated arithmetically, and the total expressed is higher than the reality, the net energy used is about 10 kW$_e$ less. Looking at **table 7.1** the pyrogas are in the output line. In the flowsheet of the system boundaries, part of the pyrogas will be used as heat/steam for the plant.

No allocation was considered. All the primary data are taken with their impact.

Chapter 6 presented the system's stages in detail (slow pyrolysis, thermal oxidizer and heat recovery, and recovery of metals). Below are the tables with input and output.

INPUT		
Materials		
Parameter	**Unit**	**Amount**
Hazardous waste (in powder)	ton/h	1.0
Tap water	ton/h	1.8
HCl (@36%)	ton/h	2.2
H_2SO_4 (@98%)	ton/h	0.4
H_2O_2 (@33%)	ton/h	0.2
$Ca(OH)_2$	ton/h	0.7
NaOH	ton/h	0.2
Air	ton/h	8.8
Energy		
Parameter	**Unit**	**Amount**
Electricity - from mix grid	kW	54.0
Electricity - from photovoltaic	kW	36.0
CH_4 (natural gas)	ton/h	2.0E-02

***Table 7.2** Input innovative scenario per FU (1 ton of hazardous waste treated).*

OUTPUT		
Materials [including **products and by-products**]		
Parameter	**Unit**	**Amount**
Precipitate 1 (50% humidity) Aluminum Chloride ($AlCl_3$)	ton/h	1.3
Precipitate 2 (50% humidity) Copper Sulphate ($CuSO_4$)	ton/h	0.6
Materials [including solid waste and liquid waste]		
Parameter	**Unit**	**Amount**
H_2	ton/h	1.0E-02
Water to treatment	ton/h	1.8
Water vapor	ton/h	0.3
Dried char	ton/h	0.3

***Table 7.3** Output innovative scenario per FU (1 ton of hazardous waste treated).*

Tables 7.2 and **7.3** collect all the input and output for each scenario. Data were normalized on the functional unit of 1 ton of hazardous waste to treatment.

As written before, for the first part of the system (the pyrolysis) the principal output is the pyrogas (in **table 7.3**), which is a mix of gas and condensable composites (42% oil and 58% gas). The pyrogas produced will go straight to the thermal oxidizer. This part of the system is made for the abatement of polluting substances through the combustion of the products at 800°C for a time higher than 2 s. For the combustion of oils (organic part), the outcome is combustion fumes at 1000°C.

These fumes formed flow to the pyrolysis itself to guarantee heat for the process. Then, part of them will go out at 500°C to a heat exchanger (water fumes) to produce hot water at 90°C that is used by the leaching processes.

From the exchanger, the fumes go out at a temperature of 250°C and then finish at the char drying. The rest of them, under the name of **water vapor,** go out from the system at 130°.

In the inventory table and, later, in the model there is no consideration of the emissions. The reason for this choice is due to their absence, because of the remotion of pollutants no important emissions were considered. In **chapter 6**, next to the final char drying some emissions are going out into the air, they are out from the system and not pollutants.

To complete the thermal oxidation an air flow is needed, together with methane (auxiliary fuel). The air entering the system is calculated arithmetically.
All the chemical reagents in the input are used for the leaching processes.
After the two leaching processes, the precipitation stage occurs, with a calculated yield of 515.2 t/y ($AlCl_3$) and 232.2 t/y ($CuSO_4$).
The consumption of water is considered almost absent, inside the system, there is a re-cycle of water, and the inventory was chosen to leave the water in and out in the same quantity.

The final assumption for the innovative pathway is that 75% of the product is recovered (Scenario 75:25). The 75% was calculated from the yield of pure metal, almost the 30% that in salt is close to 70%.

In conclusion for the mass balance a consideration about the water treatment. Water is used after the leaching process, and this may be considered water to be treated. The concentration of wastewater from industrial treatment is reported in attachment 5, the third part of D. lgs. 152/06. It is possible, with this legislation, to calculate how much water is needed to elute the concentrate in a certain range.
Further studies are needed to decide if this water can be used as a flocculant, due to the limited concentration of some residues of typical flocculant substances like $AlCl_3$.

Regarding the energy balance, the parameters from the input material are electricity and methane. The thermal energy produced internally by the thermal oxidizer does not participate in the final energy balance.
The total thermal power considered for the pyrolysis system is around 53 kW_t, this value already includes the internal losses and those connected to the char output. This is determined from the thermal power generated from the combustion of pyrogas (156 kW_t) and the combustion fumes output (108 kW_t). The oxidation of pyrogas provides the thermal energy needed for the entire system. However, around 90 kW_e (conservative value) is requested by the system. The model assumes they are taken in part from the national grid (60%). The rest (40%) is covered by the photovoltaic plan onsite. The type of photovoltaic panel installed was not clarified and the data inserted in SimaPro is from the Ecoinvent database.

8 Evaluation of the innovative scenario

The focus of this chapter is the evaluation of the environmental impacts of the innovative scenario, more specifically the contribution analysis of the single stage included.
In this section of the Thesis, the interpretation is carried out from the model scenery presented in the previous chapters: the innovative scenario. The effects on the environment, human health and resources related to the input and output flows and quantified in the intermediate impact category (*midpoint*) and final damage category (*endpoint*).

8.1 Midpoint ReCiPe 2016

The innovative scenario presented in the life cycle analysis, ***chapter 7***, is explained here with the utilization of the ReCiPe 2016 method (full description in ***chapter 5.3.1***). This methodology permits to check of the environmental weight of each scenario per impact category. The midpoint level presents 18 impact categories (shown in **Figure 5.2** with their characterization factor). However only some of them were selected for the case study: climate change, fine particulate matter formation, human toxicity, mineral resource scarcity and fossil resource scarcity. The decision to investigate those impact categories is given by the importance of them in the research, for the material used and the final avoided product. From the comprehension of the LCI, besides climate change that is one of the most widely diffused since related to the emission of greenhouse gases, the fossil and mineral resource scarcity gives a more objective point of view about the exploitation of resources (can be seen also in the presentation in ***chapter 9*** about the endpoint). On the other hand, particulate matter and toxicity are categories that reflect impacts on emissions and potential damage to human health. The latter is widely recognized as one of the most susceptible parameters when it comes to data quality and research.

- Climate change (2)

For this impact category, the damage modelling is divided into several steps (***Figure 8.1***). Each step will guide to the following one, emission of greenhouse gases (kg) will

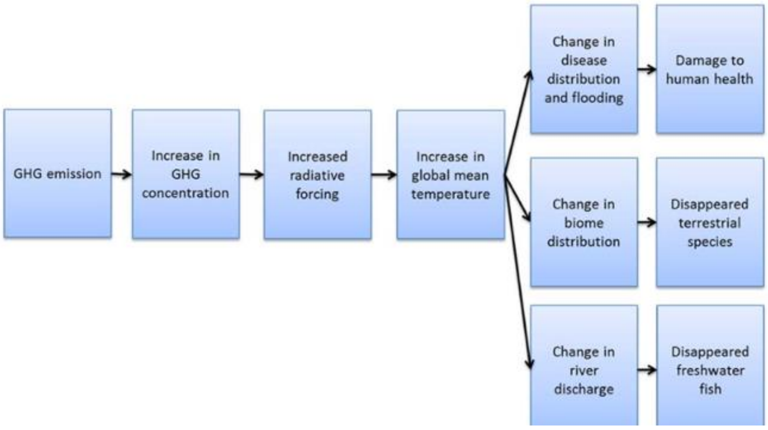


Figure 8.1 *Cause-and-effect chain from greenhouse gas emissions to human health damage and relative loss of species in terrestrial and freshwater ecosystems (2).*

increase the natural concentration (ppb), which will increment the radiative forcing capacity (w/m^2) with the consequentially increase in global temperature (C°). All the damage impact system will get to damage to human health, terrestrial ecosystem, and freshwater ecosystem.

The Global Warming Potential (GWP) is the midpoint characterization factor for climate change. The GWP describes the capacity of each gas to absorb the latent heat emitted from land, which is then released gradually into the atmosphere. GWP is measured in the mass of CO_2 eq. since the effect of each gas is normalized on that of carbon dioxide fixed equal to 1.

When it passes the endpoint, the health damage is calculated differently. Concerning human health damage is calculated in DALY – Disability-Adjusted Life Years, and it considers the increased risk of diseases like malnutrition, malaria, and diarrhoea, moreover the flood risk could lead to additional damage. Of course, tot every region in the world is affected in equal measure by all these effects. For this reason, is performed a summation of all the effects and increased temperature per region.

- Fine particulate matter formation (2)

Fine particulate matter ($PM_{2.5}$) is a mixture of organic and inorganic substances with a diameter of less than 2.5 μm. Primary and secondary aerosols in the atmosphere harm human health that can cause respiratory issues evolving to hospital admission and death (5). One of the biggest problems with $PM_{2.5}$ is that it reaches the lungs when inhaled and the aerosols are from the emission of sulphur dioxide, ammonia, nitrogen oxides and other.

WHO (World Health Organization) studies the health risks associated with particulate matter less than 10 and 2.5 (PM_{10} – $PM_{2.5}$). PM can penetrate deep into the lungs and enter the bloodstream causing heart and respiratory diseases. Both long and short-term exposure can show the symptoms of respiratory and cardio vascularity issues, especially long-term has been further linked to outcomes in lung cancer (6).

PM is also capable of entering the bloodstream causing cardiovascular (ischemic heart disease), cerebrovascular (stroke) and respiratory impacts. Both long-term and short-term exposure to particulate matter is associated with morbidity and mortality from cardiovascular and respiratory diseases. Long-term exposure has been further linked to adverse perinatal outcomes and lung cancer.

Above, in **figure 8.2** the cause-and-effect chain from the emission in the atmosphere

to the damage to human health.

A characterization factor is a dimensionless number that expresses the strength of a substance relative to the referenced substance. The characterization factor for climate change is the global warming potential and the unit is kg CO_2 per air.

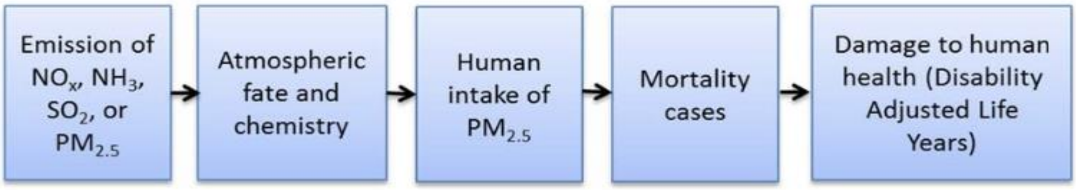


***Figure 8.2** Cause-and-effect chain, from fine dust formatting emissions to damage to human health (2).*

- Human toxicity (2)

To evaluate the potential human toxicity of a substance some aspects are taken into consideration, the internal toxicity (effect), the persistence in the environment (fate) and the accumulation in the human food chain (exposure). The effect is calculated with the damage data for humans and animals, while the fate and the exposure are calculated with a math model. This category unit measure is 1,4-dichlorobenzene equivalent to kg (characterization factor in human toxicity potential).
Figure 8.3 the cause-effect pathway, from emission to the environment.

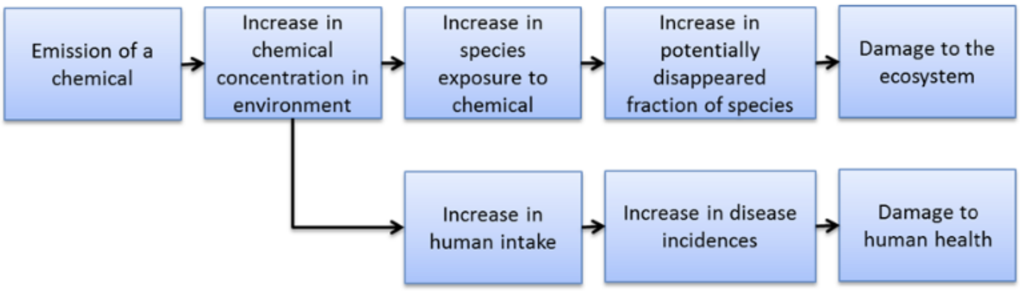


Figure 8.3 *Cause-effect pathway of toxicity (2).*

- Mineral resource scarcity (2)

For this impact category, there are several steps. All the passages, from the primary extraction of mineral resources to the surplus ore potential (SOP – which is the midpoint indicator) will lead to a surplus cost potential (SCP). SOP and SCP are the first to be explored and here there is the estimation of the damage to natural resource scarcity. The characterization point is surplus ore potential and the unit kg Cu.

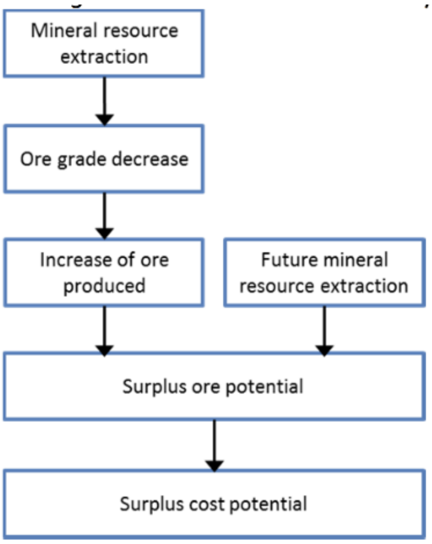


Figure 8.4 *Passage chain to SOP and SCP (2).*

To understand how many minerals there are and how to calculate the characterization factor there is to distinguish two types of the reserve. “Reserve - R” is defined as part of a resource “which could be economically extracted or produced at the time of determination” and it’s the current price and state of technology. “The ultimate recoverable resource – URR” refers to “the amount available in the upper crust of the earth that is ultimately recoverable". There are different calculations for ore extraction from pit mining or crust. Open-pit mining is preferred due to the costs, but it will most likely become depleted in the future. There are various estimates for future mineral primary production, resulting in a range of characterization factors that depend on reserve estimates.

- Fossil resource scarcity (2)

For the fossil resource category is assumed that in the endpoint modelling the fossil fuels with the lowest cost are extracted first. Because of that the increasing fossil fuels extraction will cause an increase in costs due to a change in production or to search for a lower-cost location.
The characterization factor is fossil fuel potential with the unit measure kg oil.
Figure 8.5 the pathway to the cost potential of fossil resource scarcity.

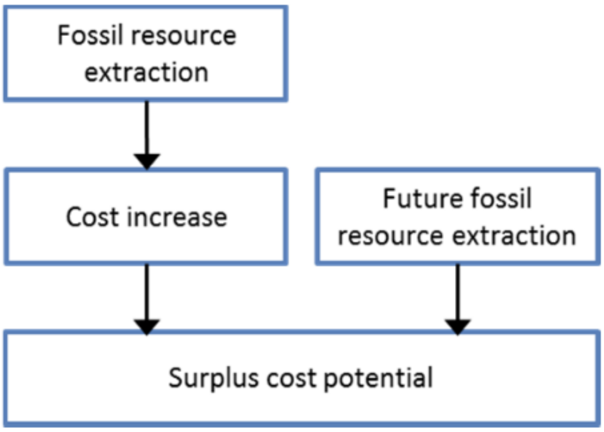


Figure 8.5 *Pathway to SOP in fossil resource scarcity (2).*

To grant greater objectivity to the LCA study, the ReCiPe 2016 method refers to the Cultural Theory concept (1). This theory, as written in **chapter 5**, considers human behaviours in two aspects: attachment to the group and respect for the rules of the group. From the five archetypes (individualist, egalitarian, hierarchical, fatalist and autonomist) just one can be chosen as a reference to low the subjective grade on the evaluation of the impacts, adding a more scientific methodology to the analysis.
In this project, the archetype used is the *Hierarchist, H* because it is the intermediate between an optimistic one (Individualist) and one with a longer period and more precautionary (Egalitarian).

8.2 Contribution analysis

Below is the result of the analysis of the Innovative Scenario, the one described previously with a percentage of avoided products equal to 75% (the rest is discharged). The category impacts are divided into 18 different ones, following the ReCiPe method, with this division is possible to directly consider the environmental weight with their measure units.
In ***Figure 8.2*** it is possible to see the different contributions of single inputs and outputs (for the complete data table refer to **annex 1**). In general, the major contribution is from

the avoided product. Even if it is just 75% of the total output, the possibility to reuse $CuSO_4$ and $AlCl_3$ is an opportunity for the company and for the environment. As explained in **chapter 6**, 75% of the product is taken from the average salt and copper that is inside the final output. The product, data taken from internal communication (3), the quantity of pure copper is 30% while the total quantity of salt formed is almost 70%, and for this reason, it was assumed as a good approximation that 75% of avoided products from the total output. **Figures 8.7** to **8.11** is it visible the importance of the recovery of these metals. The figure represents the three networks of the single impact categories (which are the ones analyzed before). The red arrows represent the impacts, while the green ones are the avoided burdens. The higher the avoided impact or impact, the bigger the arrow and the percentage. In all the categories studied the use of copper and aluminium is essential, in climate change, for example, most of the impact avoided is from the aluminium chloride while the hydrochloric acid is impacting it. On the other end, above the 0% line, 25% of copper sulphate and aluminium chloride (in dark pink and light green) and the solvent used in the leaching process, are the most impacting material used. In **Figure 8.6** it is possible to see which one of the material-product used is the most impacting. With the network analysis, the different materials and waste-product are analysed in detail. For example, one of the most impacting, in **Figure 8.6**, is HCl. From GWP, climate change, the contribution of the acid is almost 20% out of 50%, from the network in **Figure 8.7** it is seen that most of this contribution (GWP is calculated to be -502 kg CO_2 eq) is the HCl (2.42E3 kg CO_2 eq). HCl derived from the production and market of chlorine that will get its contribution probably from its processing. As mentioned in **chapter 2** in the waste management cycle there are direct and indirect impacts, with the network it is possible to see where these are and how to try to mitigate them (changing the process, the material and reagent used, …).

All the other networks show different contributions that act on the system and are represented in **Figure 8.6**.

However, it cannot be possible to proceed in different ways because to have an efficient recovery of metals the use of HCl and H_2SO_4 is essential for copper and aluminium. The removal of heavy metals from waste is not easy and leaching with acid is still one of the best possibilities (4). At this moment the replacement of one of these solvents is not possible (3), but the research is still going.

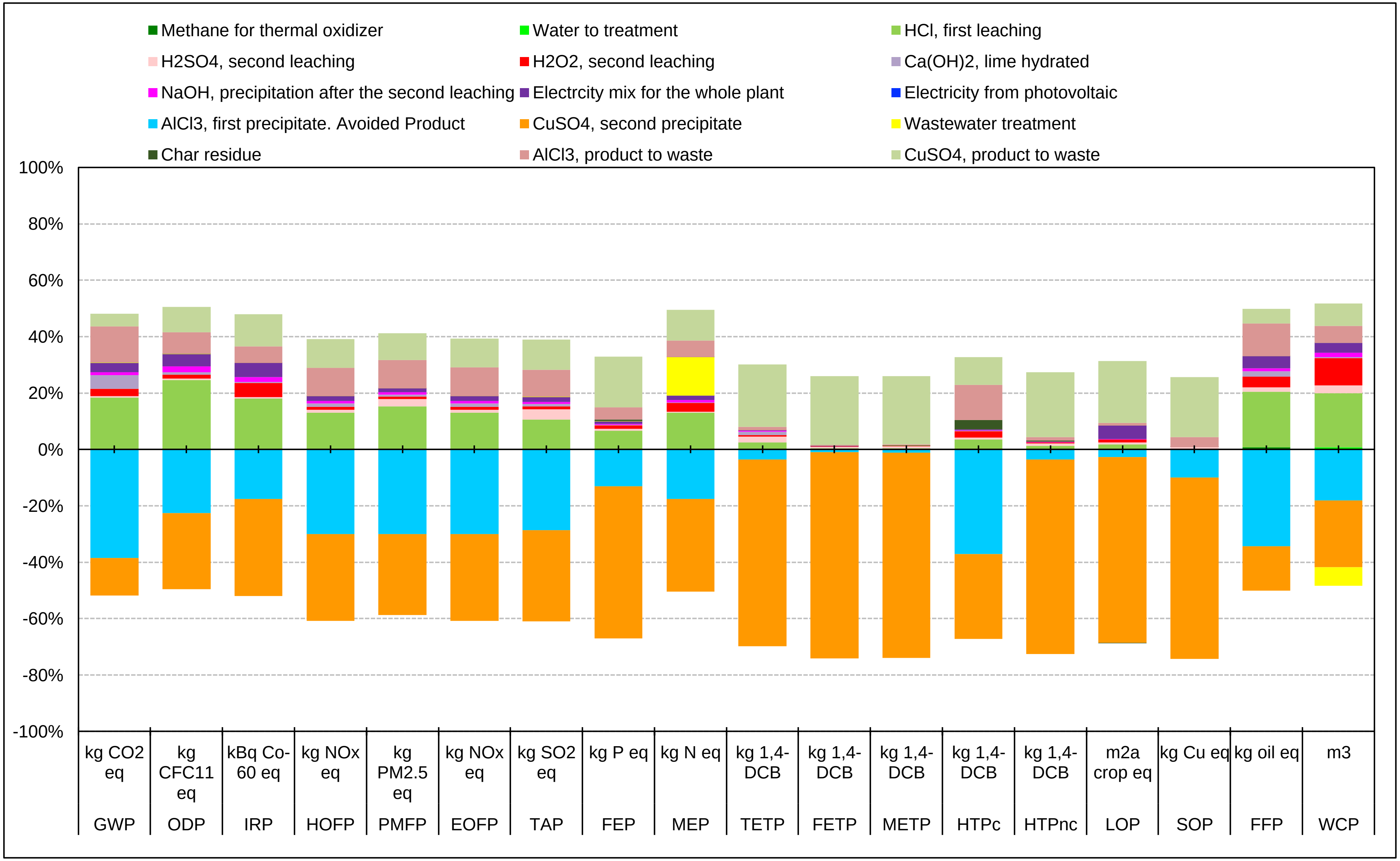


Figure 8.6 *ReCiPe Midpoint - 75% avoided product - Innovative Scenario.*

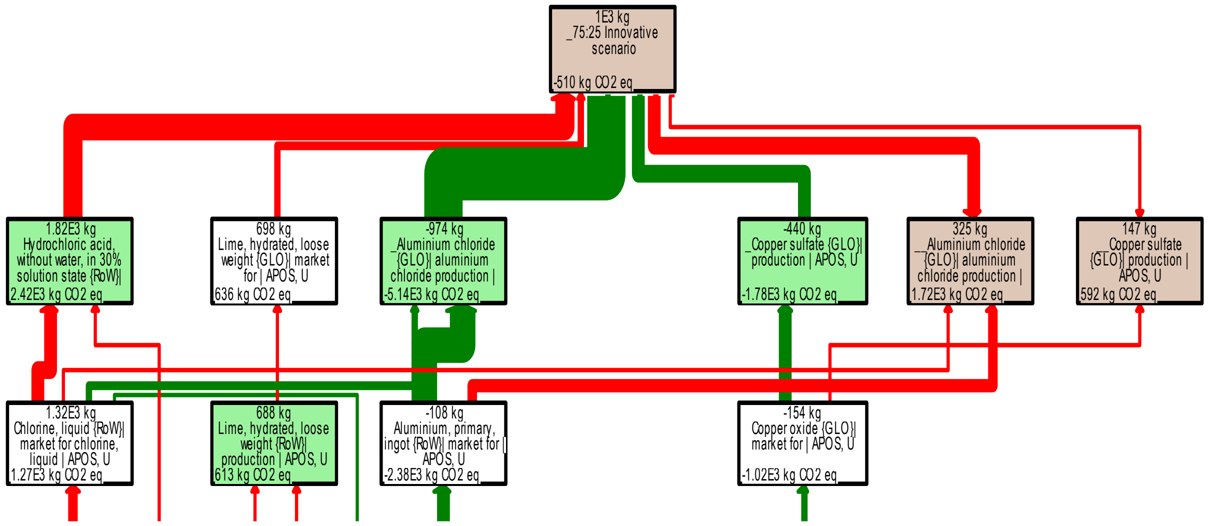


Figure 8.9 *ReCiPe midpoint - GWP network, first contributions.*

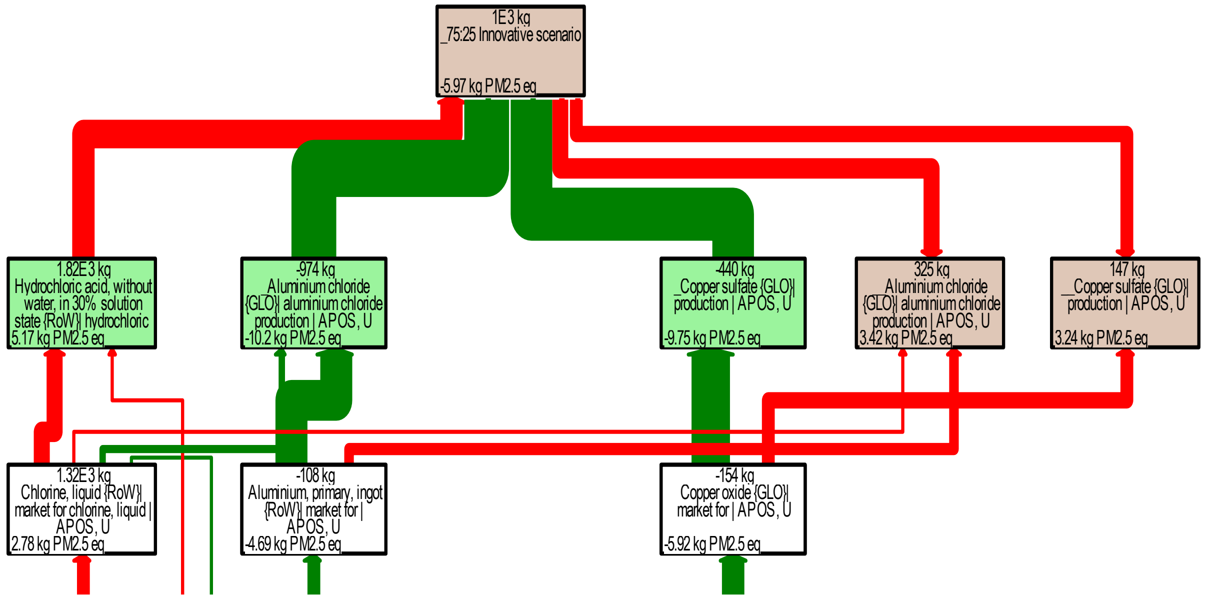


Figure 8.8 *ReCiPe midpoint - Fine Particulate Matter network, first contributions.*

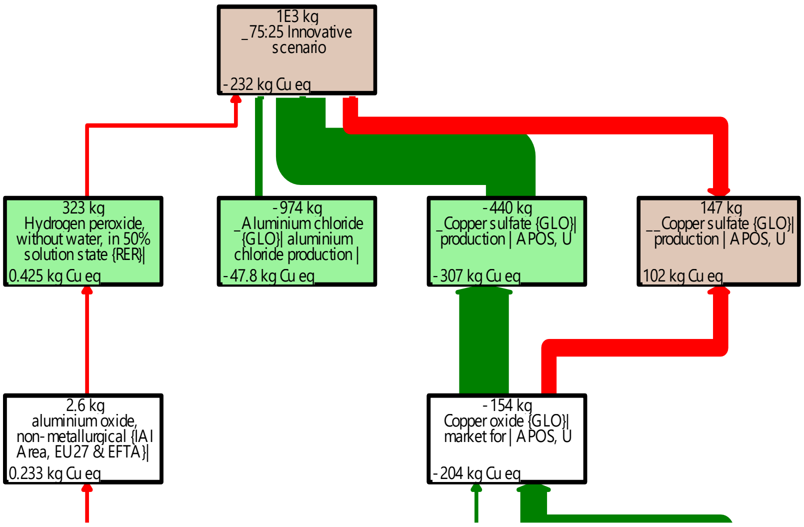


Figure 8.7 *ReCiPe midpoint - Mineral Resource Scarcity network, first contributions.*

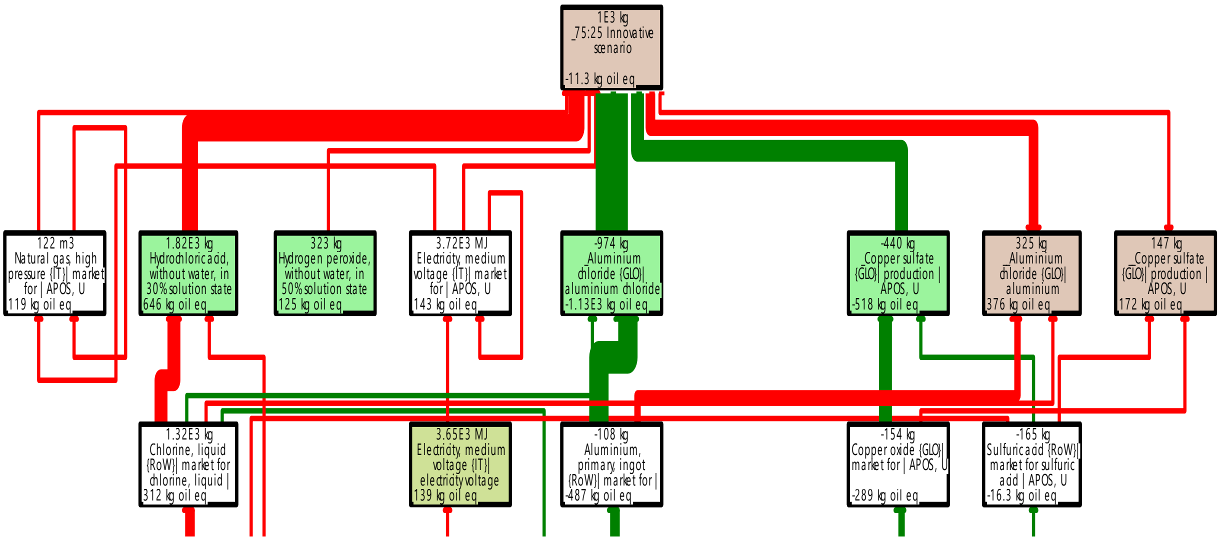


Figure 8.11 *ReCiPe midpoint - Fossil Resource Scarcity network, first contributions.*

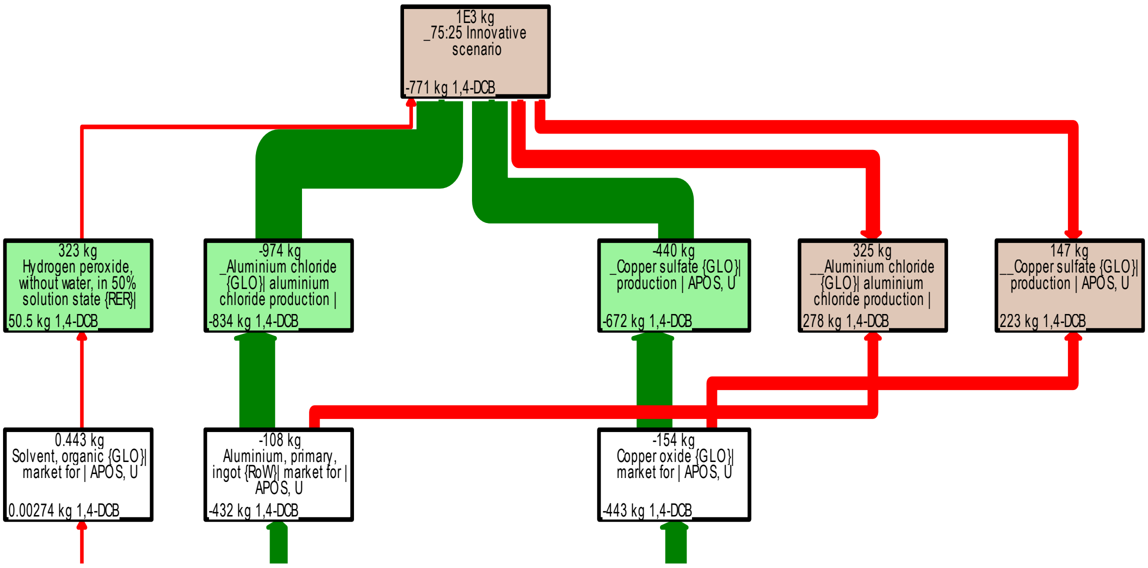


Figure 8.10 *ReCiPe midpoint - Human Carcinogenic toxicity network, first contributions.*

9 Sensitivity and uncertainty analysis (Monte Carlo)

In this chapter, a description of the alternatives applicable to the innovative scenario and a comparison with a more consolidated scenario for hazardous waste treatment (*business as usual - BAU*) are reported.
Sensitivity analysis studies the effect of input data on the results, and it can be accomplished to determine the importance of each variable or to investigate the contribution to the final score of the assumption.
The conclusion of the LCA can be quite heavily dependent on some input data, this is not necessarily a problem if the outcomes of the life cycle assessment are reliable.
Based on the results of the analysis, the conclusion can be that there is no single answer, and everything could depend on the assumption used, or also that with the assumption the scenario's situation can change and others can be better than the baseline. In this last case, it must be explained which are the conditions and assumptions and if they are valid.
With this methodology, it is possible to test the robustness of the models created and understand how some variation can affect the results. Following this principle, the LCA was recalculated assuming different scenarios.

All the analyses proposed, starting from the baseline, are based on data collected from a lab-scale prototype considering the treatment of 1 ton of hazardous waste (FU). The sensitivity analysis was focused on the number of byproducts ($AlCl_3$ and $CuSO_4$) recovered, assuming fewer amounts and creating two limited cases: Scenario 50:50 and Scenario 25:75. Then the contribution of the usage of renewable energy (100% photovoltaic system) was verified. The paragraph also collects the results from the uncertainty analysis performed by the Monte Carlo method.

9.1 Sensitivity analysis with different scenarios

As written above, two alternative scenarios were created to establish the contribution of the recovered salt of the whole impacts: Scenario 50:50 and Scenario 25:75. Results are collected in **Figure 9.1** and **Figure 9.2**. As shown, moving from the baseline (Scenario 75:25) to the alternative pathway created the portion of avoided impacts (below the line of zero) decrease with a consequent rise of the potential burdens. The reason is the amount of copper sulphate and aluminium chloride recovered within the system. From 251 t/y of char entering the leaching part of the system, the quantity of $AlCl_3$ and $CuSO_4$ are respectively 515.2 t/y and 232.2 t/y. The formulation of the first precipitate is a mix of aluminium polychloride ($AlCl_3$) and iron chloride ($FeCl_2$). The second compound was not considered in the following result and in the LCI because the quantity was lower and HCl as a reagent was calculated following the quantity and stoichiometry of aluminium. The formation of the salt is due to the leaching process, here there is the addition of other components like HCl, H_2SO_4, and so on. The data table of the single contribution is shown in **annex 2-3**. A comparison among them at the midpoint level is depicted in **Figure 9.3**. From this scheme is clear that the best process is the one investigating as a baseline Scenario 75:25. Another interesting point, in the comparison, is related to the different trends along the impact categories considered. While climate changes there is less than 20% negative for the best scenario on the other hand in human toxicity and mineral resources it is almost -100%. This is due to the recovery of the salts, especially copper, simulated as an avoided production from virgin raw materials. To explain this phenomenon in **Figure 8.9** the contribution of copper sulfate is the highest, and copper sulfate is derived from copper oxide. Therefore, avoiding the production of virgin $CuSO_4$ leads to an avoided extraction of CuO with a consequent avoidance of resources and energy consumptions within the entire chain. This leads to a sensible decrease in the environmental impacts. The same happens in **Figure 8.11** with Human Toxicity.

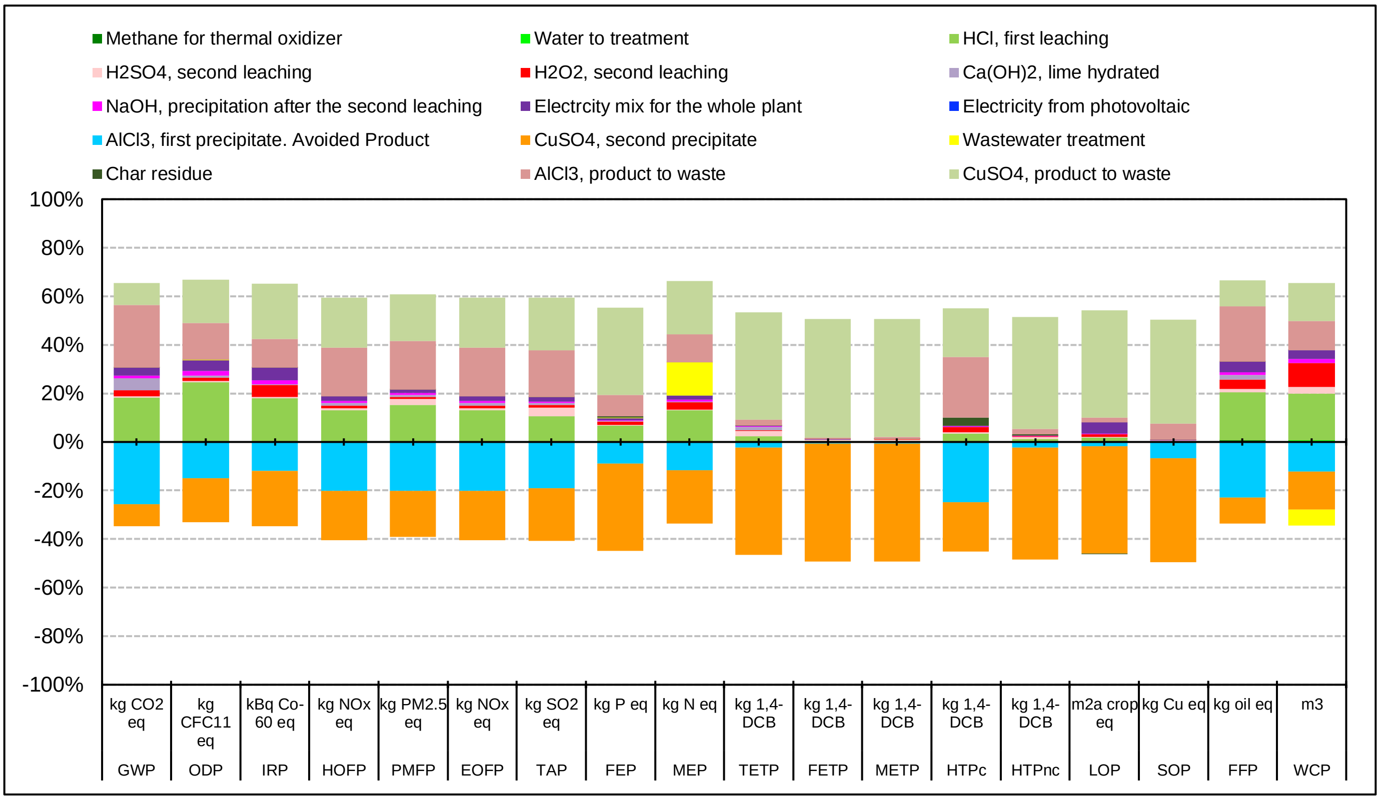


Figure 9.2 *LCIA midpoint ReCiPe 2016 – Scenario 50:50 (innovative scenario with 25% avoided product).*

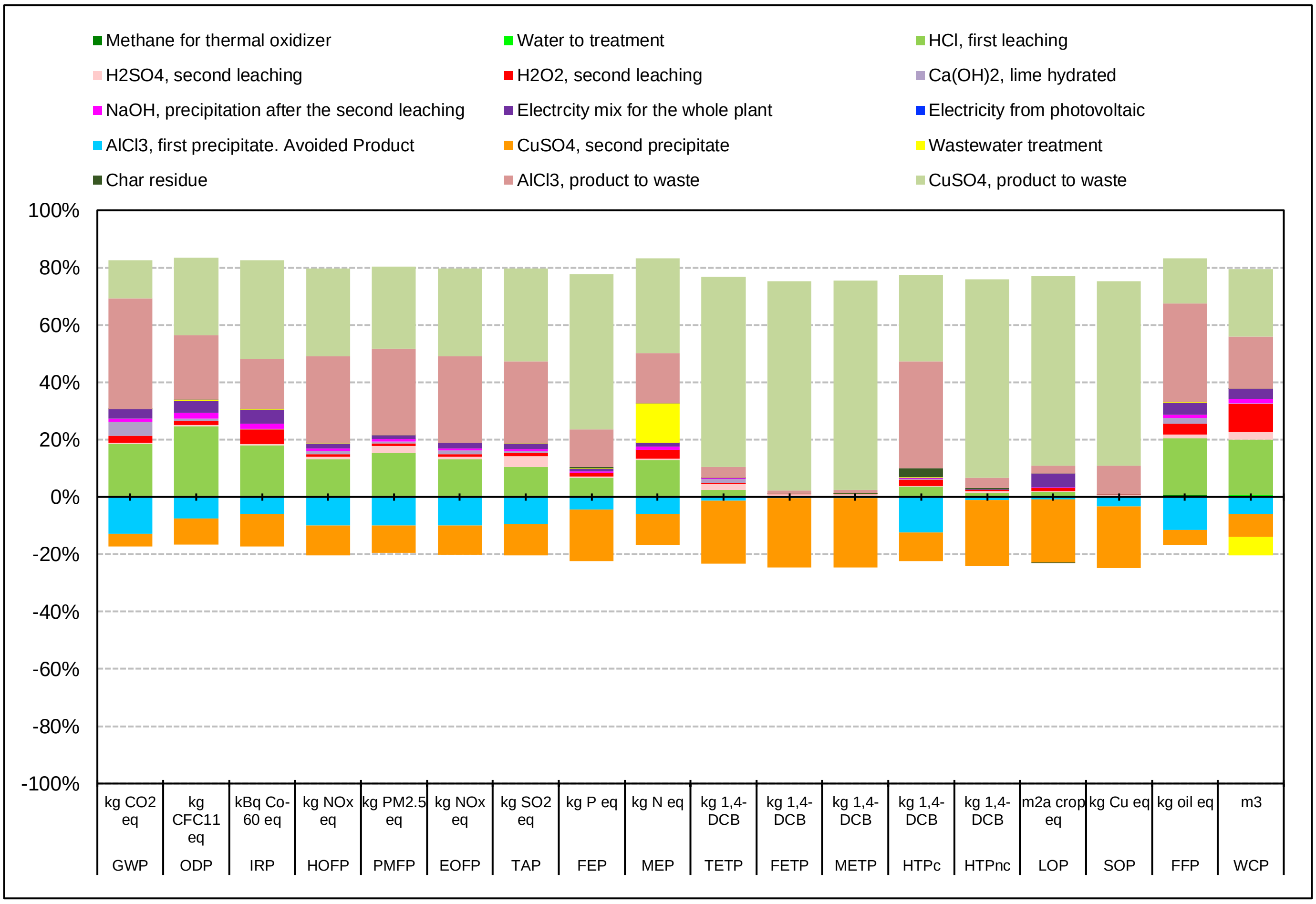


Figure 9.1 *LCIA midpoint ReCiPe 2016 – Scenario 25:75 (innovative scenario with 50% avoided product).*

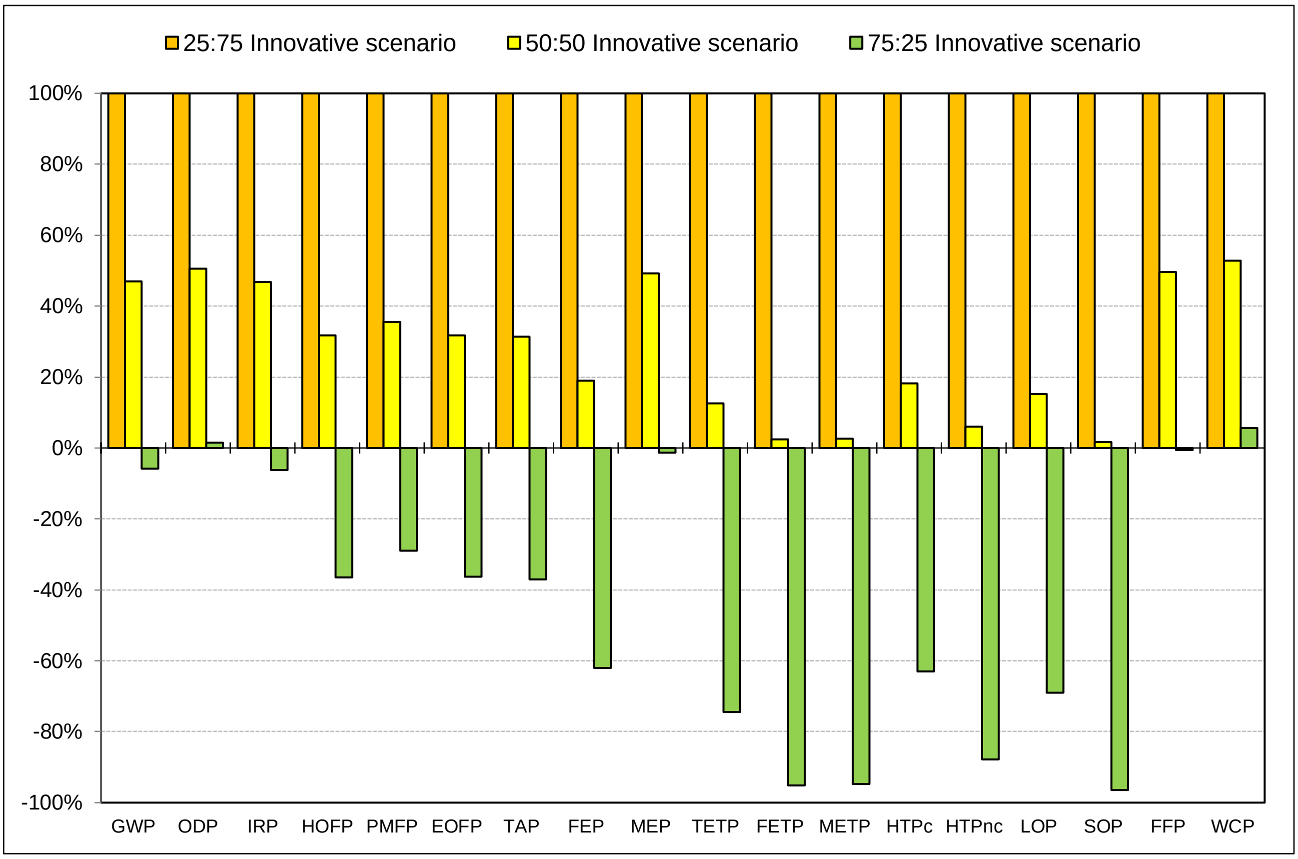


Figure 9.3 *LCIA midpoint ReCiPe 2016 – comparison between the three scenarios: i) 25:75 (orange), ii) 50:50 (yellow) and iii) the baseline 75:25 (green).*

Then, a comparison with a traditional scenario was performed to identify the competitiveness of the innovative process with respect to the incineration of hazardous waste to produce steam. The BAU process represents a typical procedure for the treatment of hazardous waste in Italy, as explained in the procedure in the ISPRA report for special waste for the different types of end-of-life treatment (7).

Figure 9.4 shows the results at the midpoint level. As depicted, the greater contribution to all the categories is associated with the RDF (Refuse Derived Fuel). This is because a small amount of the impacts related to the supply chain of the materials used as fuel were allocated to the system. Different from a zero-burden approach, the model chosen is more conservative from an environmental point of view. This approach was selected since the incineration plant is a waste-to-energy (WtE) technology that burns waste to produce steam then recycled within the plant (energy carrier for the process itself). The "emission and waste management", pink label, represents all the direct emissions in the ecosystem (air, water, and soil) as well as all the waste management due to the incineration plant. The steam derived from them is the thermal energy generated from the incineration of waste. The thickening agent is an auxiliary agent introduced to make the RDF compatible with the treatment.

The comparison among the different solutions (**Figure 9.5**) shows that the traditional scenario is the most impactful in terms of global warming, fine particulate matter, and fossil resource scarcity.

In terms of human toxicity, non-carcinogenic and mineral resource scarcity the worst is Scenario 25:75 in which 25% of salts are landfilled. This is due to the presence of leaching reagents and products to waste that is higher than in the other scenarios.

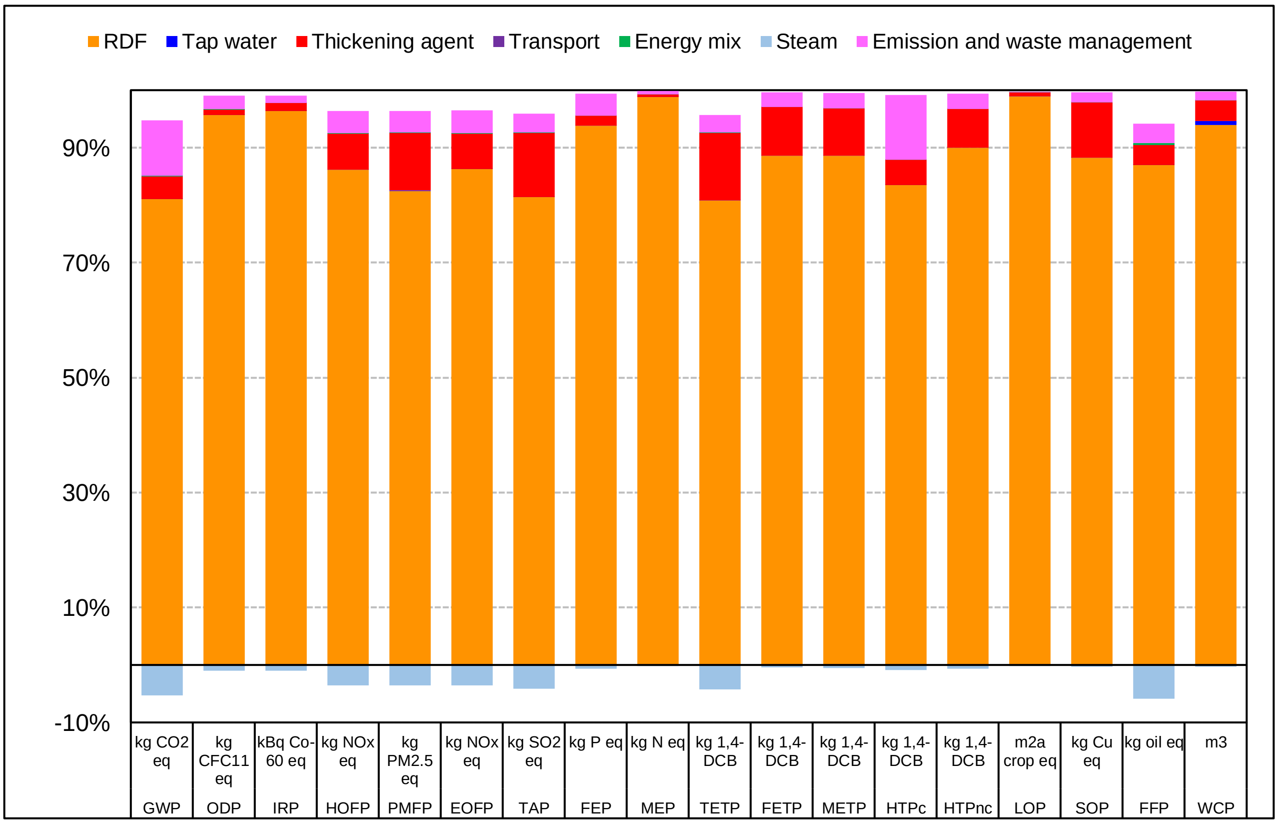


Figure 9.4 *LCIA midpoint ReCiPe 2016 – BAU scenario.*

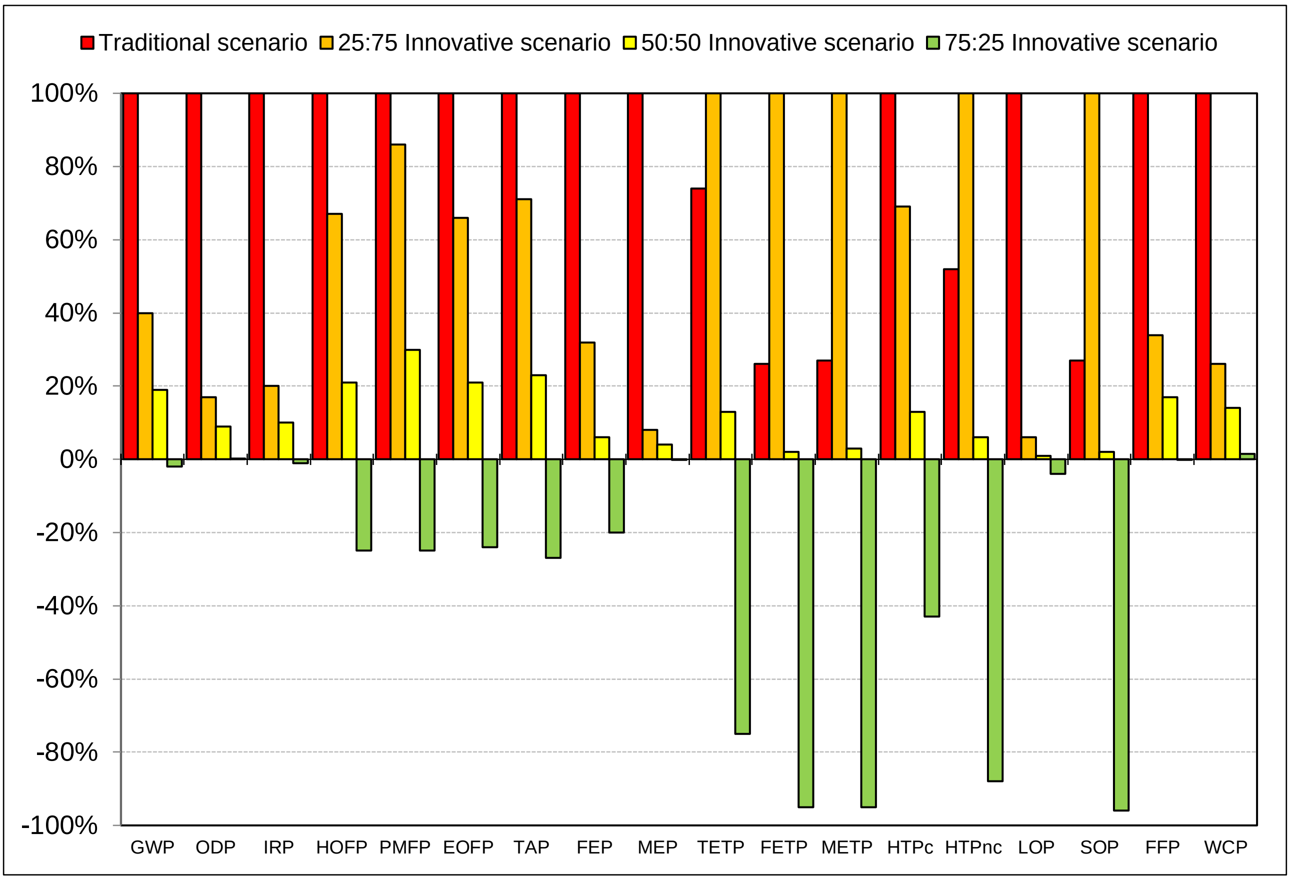


Figure 9.5 *LCIA Midpoint ReCiPe 2016 - comparison between the four scenarios: i) BAU (red); ii) 25:75 (orange), iii) 50:50 (yellow) and iv) the baseline 75:25 (green).*

In the next analysis, two different assumptions were made. The first is related to the plant location.

The baseline scenario assumes locating the innovative technology inside the company boundaries (Italmetalli plant in Bologna). In this case, no transportation was added since the waste is assumed to be treated internally.

To verify the contribution of the distance on the overall impact, an alternative scenario was created adding 410km with respect to the baseline. In this case, it was imagined installing the technology in Rome, the other site plant of Italmetalli (**Figure 9.6**). The analysis has revealed no significant repercussions on the system, especially on the impact category considered. Therefore, the innovative scenario remains competitive within 410km.

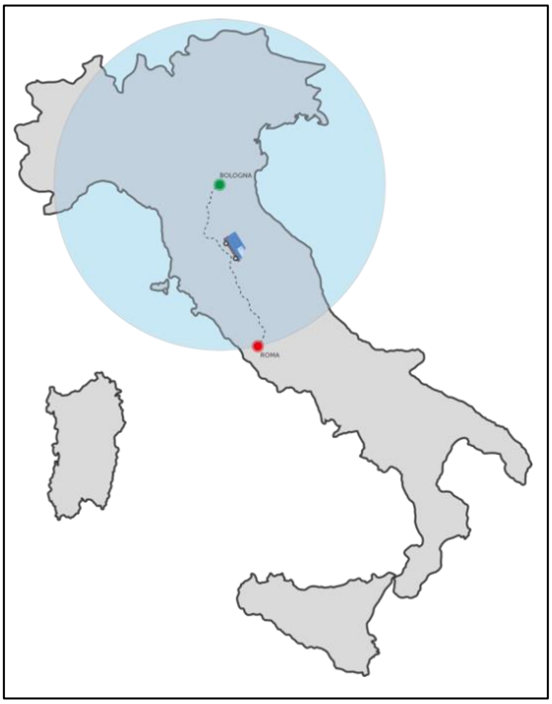


Figure 9.6 *Added transport Bologna-Roma.*

The second hypothesis is about the electricity used for the whole plant.

According to the baseline scenario, only 40% of the whole consumption is right now covered by a photovoltaic system. Therefore, a further scenario was created assuming the electricity is 100% produced internally through photovoltaic panels (Scenario 75:25_100%PV).

Figure 9.7 shows the representation in the histogram of the midpoint categories, the impact of the photovoltaic is almost nonvisible in the graphs if compared with **Figure 8.6**. However, a further visualization (**Figure 9.8**) shows that Scenario 75:25_100%PV could have benefits in all the categories strictly related to the exploitation of fossil fuels, like climate change (GWP) has -50% with PV, ozone depletion and ionizing radiation (ODP and IRP) are both with a difference of -70% and -60%. The fossil fuel potential FFP passes from -10% to -100%, with a difference of 90%. Of course, this is because the photovoltaic has a big impact on this result. Unfortunately, the water consumption WCP is the opposite, photovoltaic uses a modest amount of water to function.

As written at the beginning of this chapter even if an assumption has better results there are many things to consider, like the background of the hypothesis. In this case, if the company is suitable for working with 100% energy from solar panels.

Photovoltaic is the most rapidly expanding technology for producing electricity worldwide. There is an impressive improvement in the environmental impacts and costs since 2005. In addition, moving the manufacturing in China the costs decreased more and more. A study conducted by Stamford and Azelaic from data taken between 2005 and 2015 says that the reduction, for the production, was about 15-21% average of the total GWP and 15-74% in other environmental impacts (with the toxicity one of the highest for the metal production chain). On the other hand, shifting the production in China (the above data were from Europe) changed some of the environmental impacts, in fact, 9-13% worse than those manufacturing, for example, in Germany. China's regulations are far from Europe's, and it is possible that some results were underestimated (1).

In conclusion, when an assumption for a sensitivity analysis is made it can be better or worse based on the considered outline, but there is more to be taken into consideration, in this case, 100% of photovoltaic could be good for the company looking at just the contribution analysis but behind it, there are costs and the impact of the manufacturing itself.

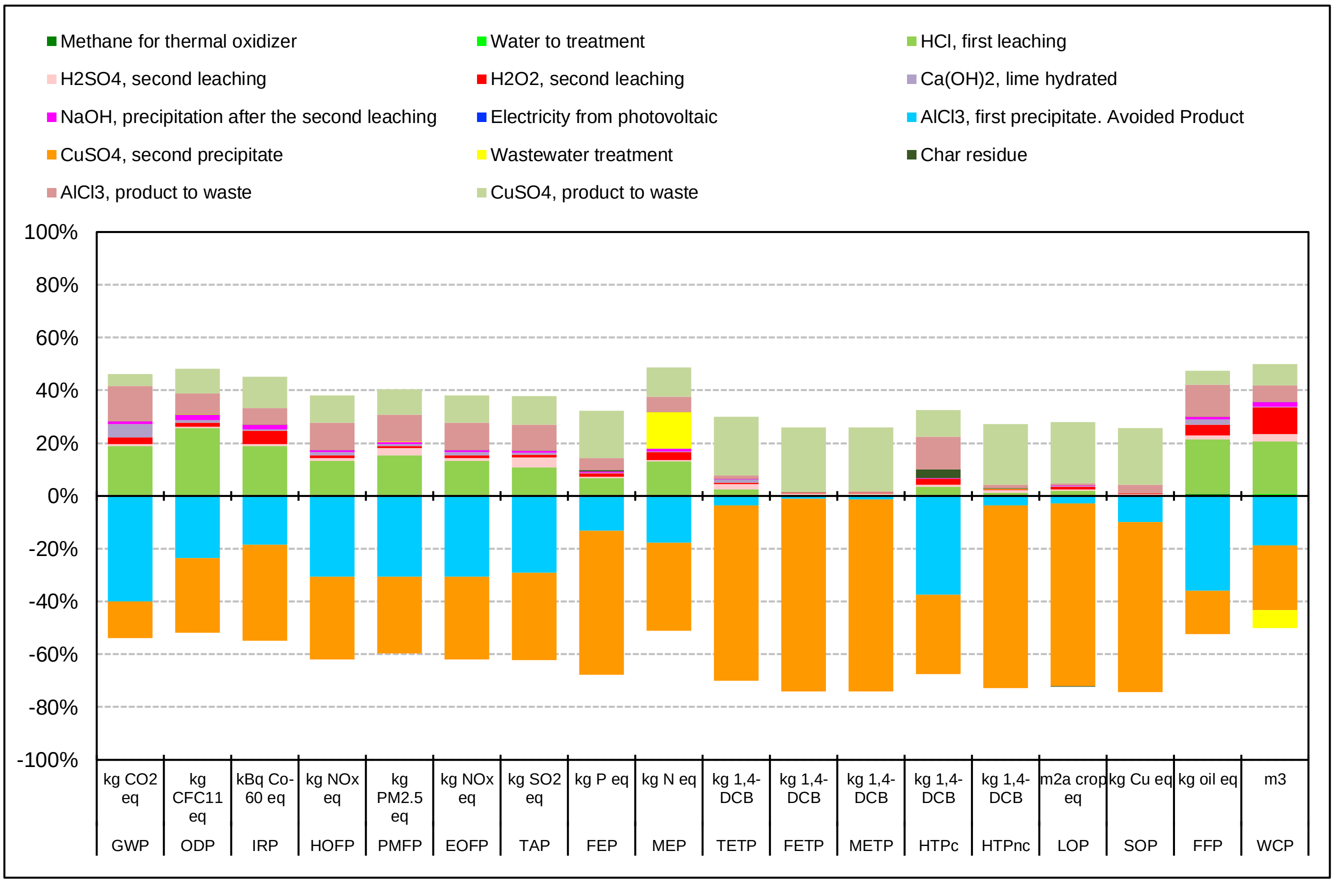


Figure 9.7 *LCIA midpoint ReCiPe 2016 – Scenario 75:25_100%PV.*

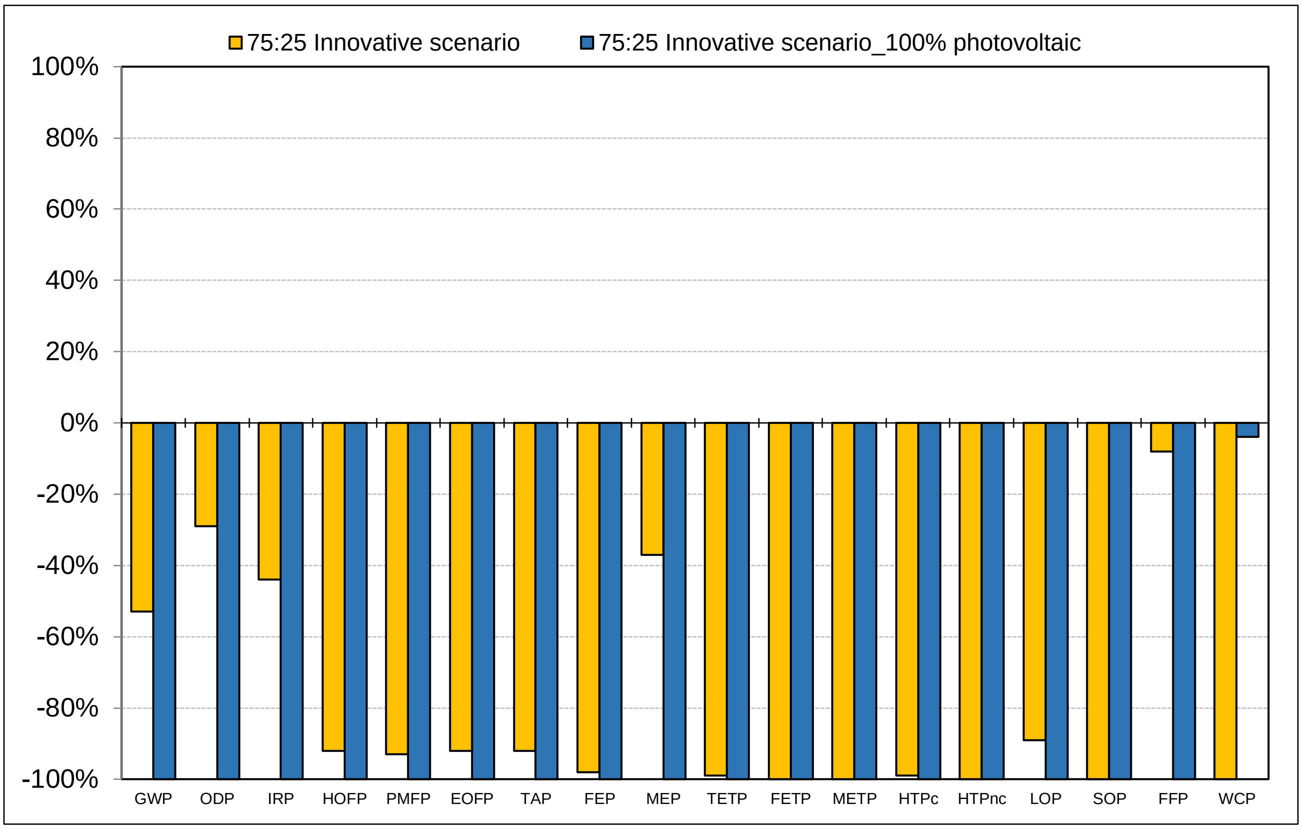


Figure 9.8 *LCIA midpoint ReCiPe 2016 - comparison between Scenario 75:25 and Scenario 75:25_100%PV.*

As a final comparison, the endpoint single score was calculated (**Figure 9.9** and **Table 9.1**). For the single score, the measuring unit becomes the point (Pt). Single score permits the quantitative comparison between the damages caused by the same categories and, if summed up, can give an indication of the environmental impacts of each analyzed scenario (in this case i) BAU; ii) 25:75, iii) 50:50 and iv) the baseline 75:25).

Damage category	Unit	Traditional scenario	25:75 Innovative scenario	50:50 Innovative scenario	75:25 Innovative scenario
Total	Pt	903.7	677.7	176.2	-323.7
Human health	Pt	818.2	657.8	169.1	-318.1
Ecosystems	Pt	69.8	15.8	5.1	-5.5
Resources	Pt	15.6	4.1	2	-0.1

Table 9.1 *LCIA endpoint ReCiPe 2016 - Single score comparison between the four scenarios: i) BAU; ii) 25:75, iii) 50:50 and iv) the baseline 75:25.*

Moreover, the choice to include the single score at the end is because the last one alone could not give an accurate interpretation. Only a combination of midpoint and endpoint can assist in a better explanation of the results and support the decision-making process (2).

In this final comparison, it is clear the distance between the traditional scenario to the baseline.

The BAU scenario shows how its endpoint factors present a higher Pt compare to the other one. Endpoint factors calculate the damages in three categories: human health, ecosystem, and resources.

Knowing that in the traditional scenario, the only product avoided is the steam produced as thermal energy, it is clear why all three categories are so high.

In **Table 9.1** is possible to clearly see the difference, the majority is the ecosystem damage. In the traditional scenario is about 70 while in the other it almost not existing. That is because the evaluation of the damages to the environment that can cause the traditional scenario is higher.

The 75:25 scenario is below zero, which means that from an endpoint category point of view, the final damage that this scenario has is the best possible scenario for human health, ecosystem, and resources.

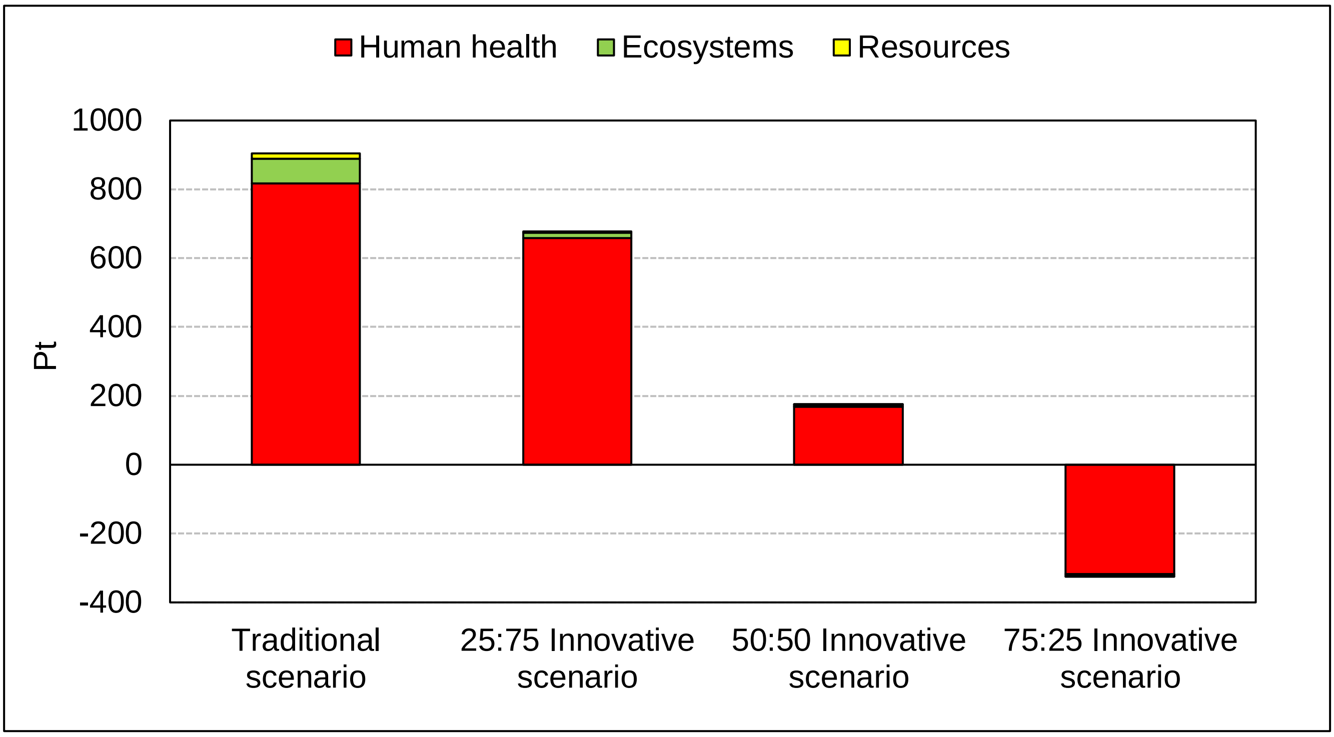


***Figure 9.9** LCIA endpoint ReCiPe 2016 - Single score comparison between the four scenarios: i) BAU; ii) 25:75, iii) 50:50 and iv) the baseline 75:25.*

9.2 Uncertainty Analysis

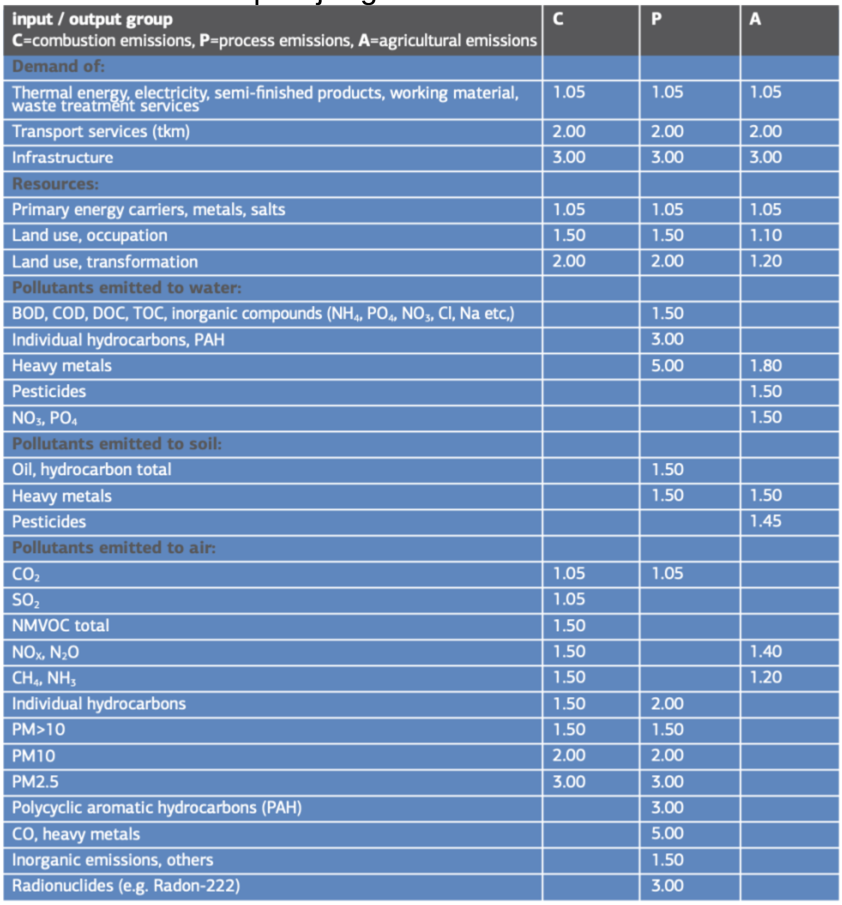
Uncertainty analysis is applied to determine how the variability of the parameters and their quality can affect the resulting outcomes. The ecoinvent database (**chapter 5**) provides a quantification of the uncertainty distribution. The database provides a standard value with the uncertainty information, that can be interpreted as a "best guess" value. The best one is decided by sampling different measurements, and this is usually the mean value of a lognormal distribution. In a lognormal distribution, the square of the geometric standard deviation covers the 95% confidence interval that is estimated with Equation 9. 1. U parameters are those reported in the "Pedigree matrix" developed by Weidema (3) (**chapter 4**). They are five criteria plus the basic uncertainty factor. The 95% confidence interval is calculated using the following equation (4):

$$\mathrm{SD_g}^{95}=\sigma_g^{2} = exp^{\sqrt{[\ln(U1)]^2+[\ln(U2)]^2[\ln(U3)]^2[\ln(U4)]^2[\ln(U5)]^2[\ln(Ub)]^2}}$$

Equation 9.2 *Standard deviation based on the Pedigree matrix (4).*

The factors U_1 to U_5 refer to the scores in **table 4.1**: reliability (1), completeness (2), temporal correlation (3), geographical correlation (4) and further technology (5). The factor U_b refers to the basic uncertainty factor.

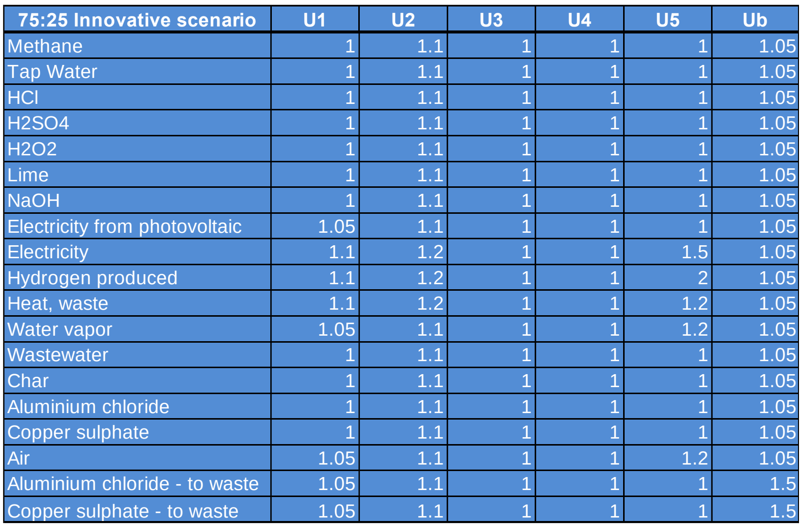
The basic uncertainty factor U_b can be derived from the following table. This basic uncertainty factor is based on expert judgment.



input / output group **C**=combustion emissions, **P**=process emissions, **A**=agricultural emissions	**C**	**P**	**A**
Demand of:			
Thermal energy, electricity, semi-finished products, working material, waste treatment services	1.05	1.05	1.05
Transport services (tkm)	2.00	2.00	2.00
Infrastructure	3.00	3.00	3.00
Resources:			
Primary energy carriers, metals, salts	1.05	1.05	1.05
Land use, occupation	1.50	1.50	1.10
Land use, transformation	2.00	2.00	1.20
Pollutants emitted to water:			
BOD, COD, DOC, TOC, inorganic compounds (NH_4, PO_4, NO_3, Cl, Na etc,)		1.50	
Individual hydrocarbons, PAH		3.00	
Heavy metals		5.00	1.80
Pesticides			1.50
NO_3, PO_4			1.50
Pollutants emitted to soil:			
Oil, hydrocarbon total		1.50	
Heavy metals		1.50	1.50
Pesticides			1.45
Pollutants emitted to air:			
CO_2	1.05	1.05	
SO_2	1.05		
NMVOC total	1.50		
NO_X, N_2O	1.50		1.40
CH_4, NH_3	1.50		1.20
Individual hydrocarbons	1.50	2.00	
PM>10	1.50	1.50	
PM10	2.00	2.00	
PM2.5	3.00	3.00	
Polycyclic aromatic hydrocarbons (PAH)		3.00	
CO, heavy metals		5.00	
Inorganic emissions, others		1.50	
Radionuclides (e.g. Radon-222)		3.00	

Table 9.2 *Basic uncertainty depending on the type of data. Taken from (5).*

The next table is the pedigree matrix with arbitrary scores of the innovative scenario.



75:25 Innovative scenario	U1	U2	U3	U4	U5	Ub
Methane	1	1.1	1	1	1	1.05
Tap Water	1	1.1	1	1	1	1.05
HCl	1	1.1	1	1	1	1.05
H2SO4	1	1.1	1	1	1	1.05
H2O2	1	1.1	1	1	1	1.05
Lime	1	1.1	1	1	1	1.05
NaOH	1	1.1	1	1	1	1.05
Electricity from photovoltaic	1.05	1.1	1	1	1	1.05
Electricity	1.1	1.2	1	1	1.5	1.05
Hydrogen produced	1.1	1.2	1	1	2	1.05
Heat, waste	1.1	1.2	1	1	1.2	1.05
Water vapor	1.05	1.1	1	1	1.2	1.05
Wastewater	1	1.1	1	1	1	1.05
Char	1	1.1	1	1	1	1.05
Aluminium chloride	1	1.1	1	1	1	1.05
Copper sulphate	1	1.1	1	1	1	1.05
Air	1.05	1.1	1	1	1.2	1.05
Aluminium chloride - to waste	1.05	1.1	1	1	1	1.5
Copper sulphate - to waste	1.05	1.1	1	1	1	1.5

Table 9.3 *Pedrigree matrix arbitrary scores - innovative scenario.*

This last part of the chapter is about the uncertainty analysis, and this part is performed on the midpoint impact categories, the same explained at the beginning of this chapter. The choice to use the midpoint categories is from the decision to look more precisely into the contribution of single impact categories. Especially the one presented before.
As written above the uncertainty analysis shows the variability and how it can change the outcomes, in the figures below it is interesting the result, especially the error bars in toxicity: in human carcinogenic and non-carcinogenic.
The error shows are important for each scenario, from the traditional to the baseline. This is due to the robustness of the parameter. The major difference is in the human health parameter, a category between everything that is the highest because it has also the lowest robustness.
Human toxicity is a difficult parameter to quantify, it depends on many variables and not all of them can be schematized (6).
In the different figures, there were no surprises from the impact categories, it is a confirmation of the initial assumption.
A particularity about one, **Figure 9.13**, the mineral resource scarcity is that the 25:75 Scenario reaches an impact higher than the others. As the toxicity the robustness of the characterization factor of the mineral scarcity is low, this can directly influence the error bar. The higher quantity of salt treatment, the higher the impact on mineral scarcity and the higher the uncertainty bar.
This happens because in this process 75% of the product is waste, going to treatment and not recovered. Here the percentage of copper and other metals is higher than the rest.

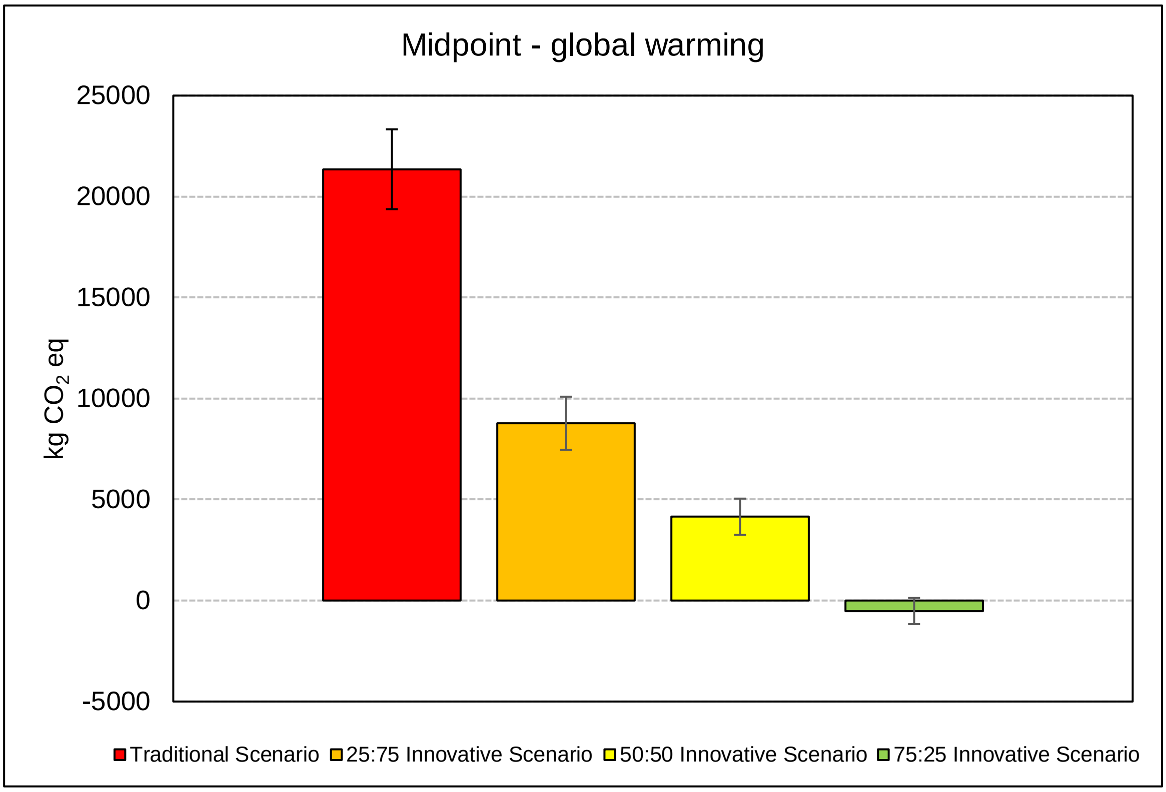


Figure 9.10 *Climate change.*

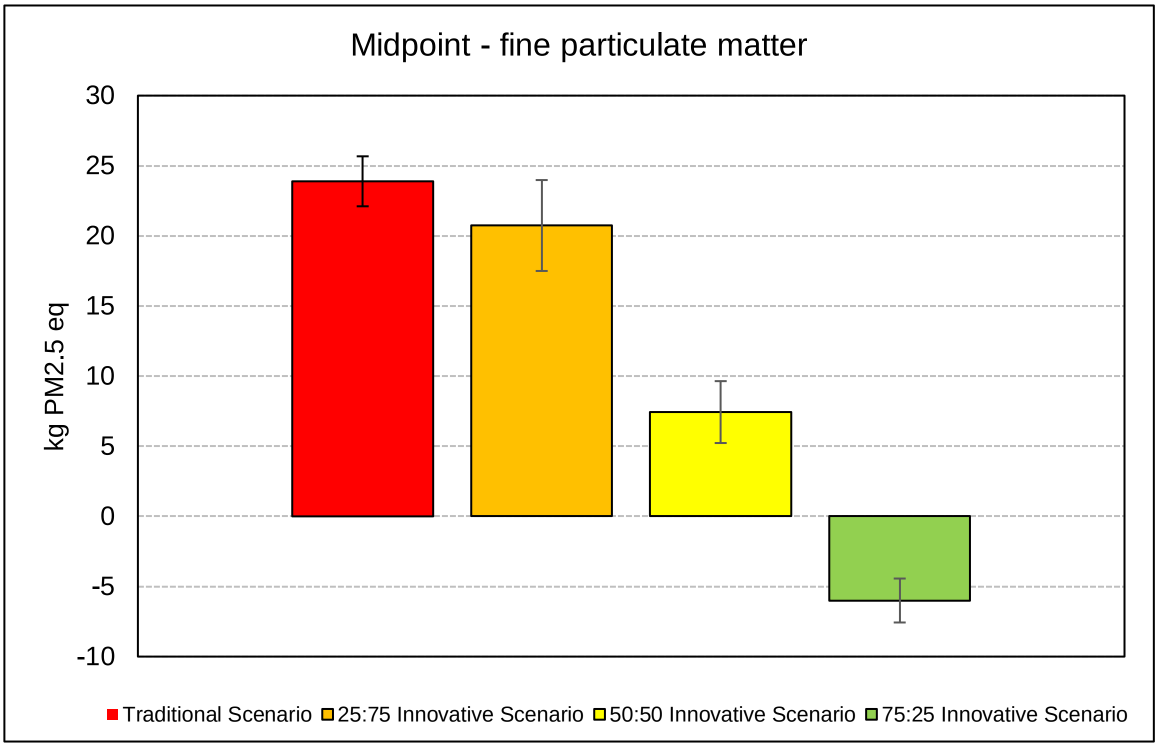


Figure 9.11 *Fine particulate matter.*

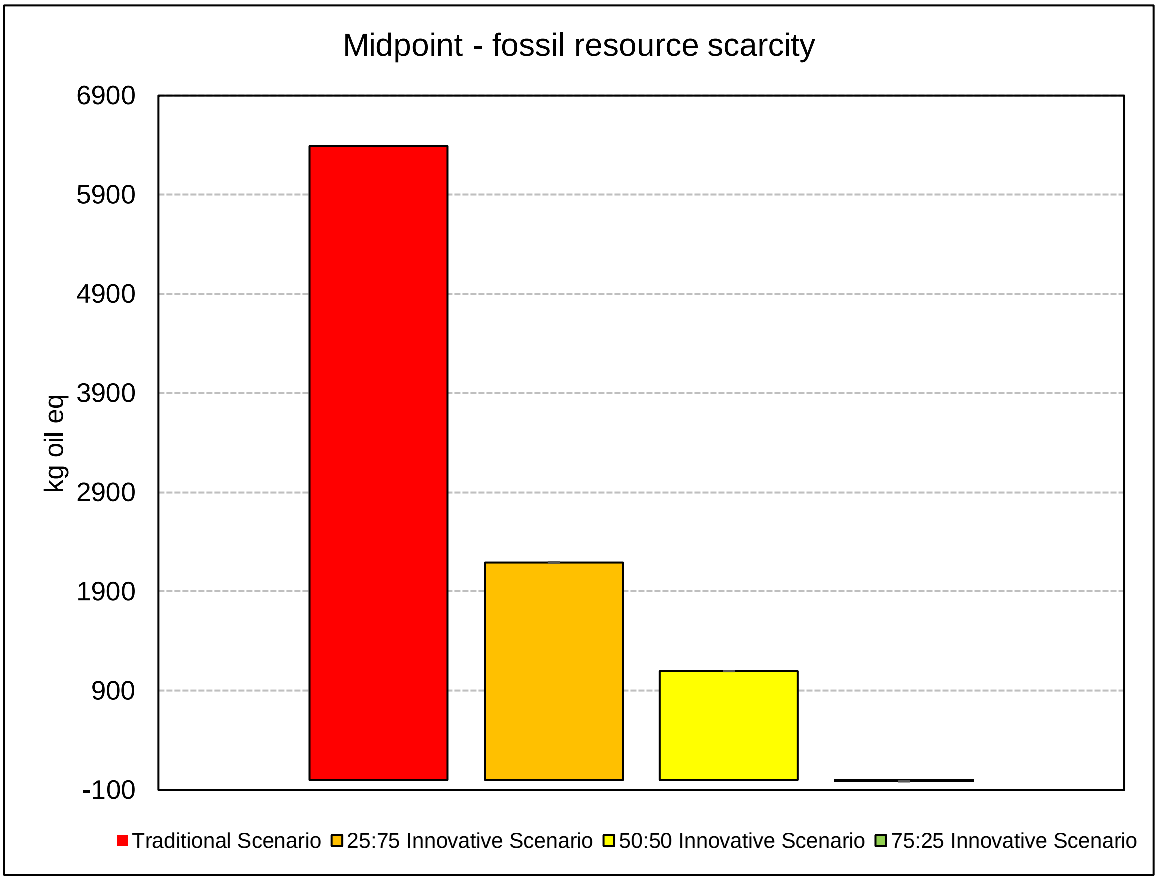


Figure 9.12 *Fossil resource scarcity.*

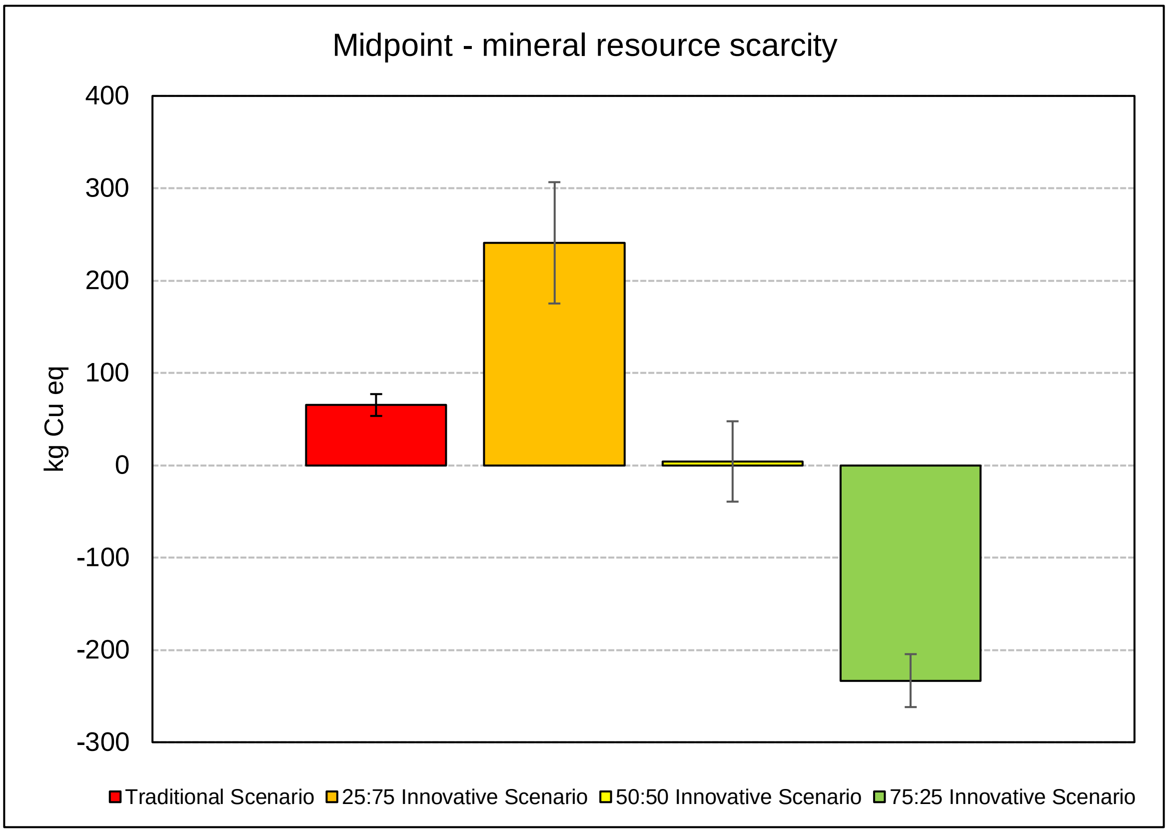


Figure 9.14 *Mineral resource scarcity.*

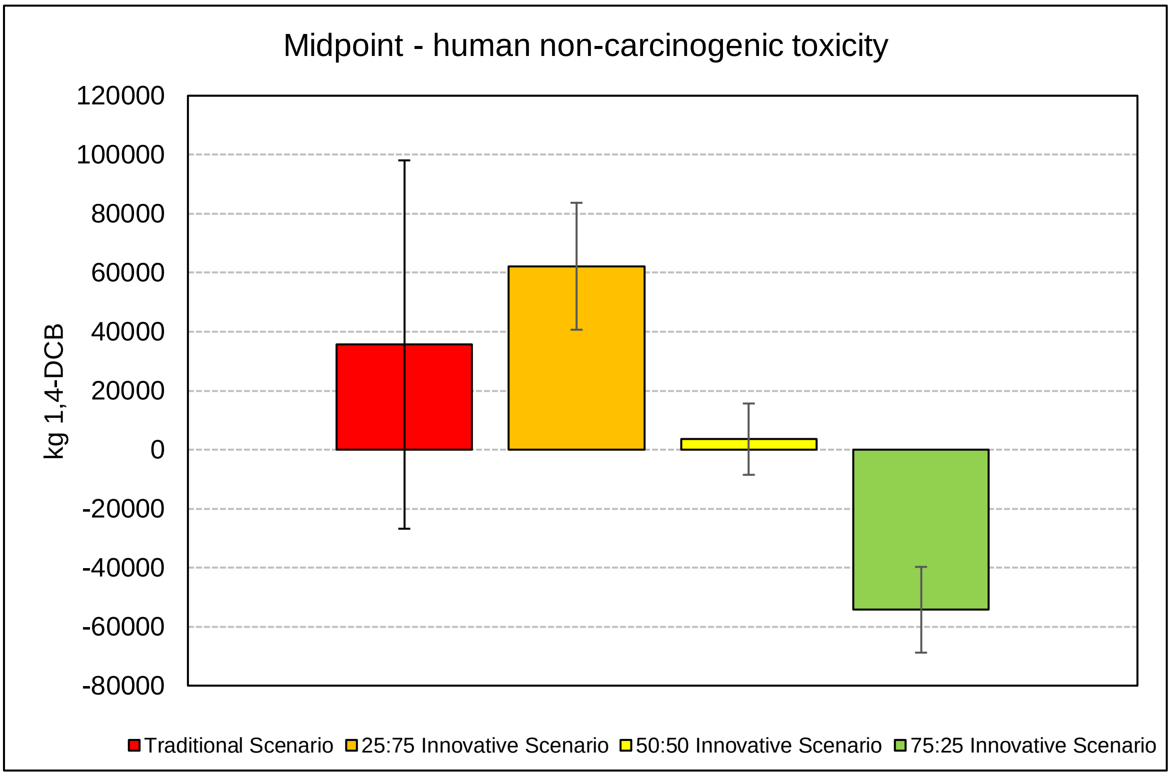


Figure 9.13 *Toxicity – non carcinogenic.*

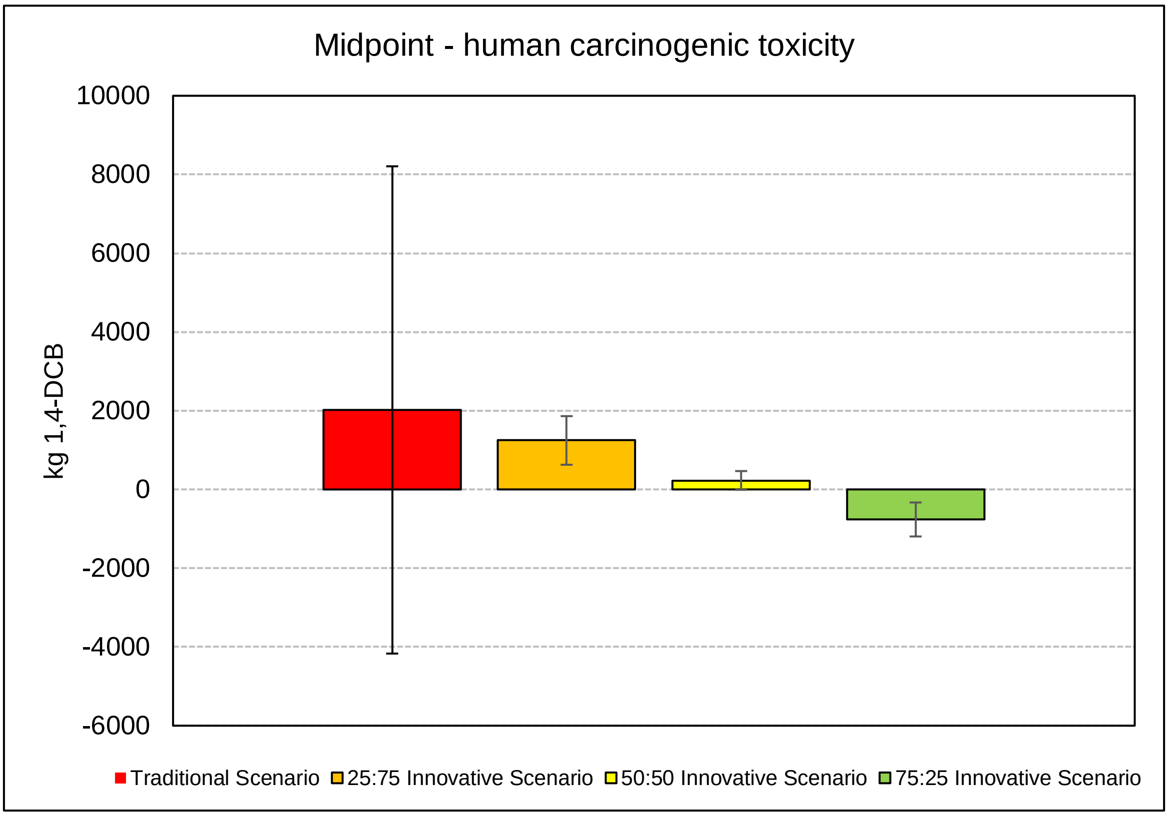


Figure 9.15 *Toxicity - carcinogenic.*

10 Conclusion

Based on the analysis conducted in this Thesis, which intended to study the environmental applicability of new technology to reduce the quantity of waste disposed of and increase the potential recovery of valuable materials, it can be concluded that incorporating material recovery into hazardous waste treatment processes using life cycle assessment methodology provides significant environmental benefits.

The study, in collaboration with Italmetalli, focused on the introduction of a different way of treatment of hazardous waste derived from powdery scrap formed after the recovery of metals, from shredding. It represents the last waste flow from the entire recovery process.
The innovation regarding this *new approach* is the idea of material recovery itself. First, this could help with the removal of hazardous products from the final waste and there is room for improvement regarding the char, the cost of disposal of the residual solid, or its valorization, which plays a fundamental role in the economic sustainability of the proposed process. In addition to that the final scope of this project was the removal and recovery of material, the metals remained in the waste powder from the Italmetalli process.
The process ends with the formation of two products: $AlCl_3$ and $CuSO_4$, that can substitute virgin metals. The procedure that accompanies these two *avoided* products is not environmentally friendly. The use of leaching still must improve, it uses sulfuric and chloride acid and most of the final environmental impacts are due to their usage. However, these salts, once purified, can both be used in other industries. Copper sulphate is largely used in the agricultural sector, and aluminium chloride is useful in the production of metal aluminium or the manufacturing of rubber, and lubricants...
The market for poly aluminium chloride (PAC) will grow at a Compounded Average Growth Rate (CAGR) of 7.8% from 2021 to 2027, this is because is widely used as a flocculant in wastewater treatment, in producing deodorant and others. With the increase of wastewater treatment, the use of PAC will increase too (1). $CuSO_4$ market share is expected to increase by 80.56 metric tons from 2021 to 2026, and the market's growth will accelerate at a CAGR of 5.6% (2).
Their recovery could be helpful both for the environment and for the company.

The application of LCA methodology helps not just to provide full comprehension and quantification about the environmental impacts related to the system is also performed to obtain different information from the process. For the modulation phases of each scenario, the software SimaPro version 9.4.02 Ph.D and the database ecoinvent 3.7.1 were used. For the first analysis, about the 75:25 innovative scenario (where 75 is the percentage of avoided products) a contribution analysis was chosen to introduce the different impact categories, explored with the ReCiPe 2016 method at the midpoint level.
The contribution helps to understand better how each material is part of the single impact. To conclude the case study the sensitivity and uncertainty analyses were carried out to look at possible, different, pathways. The best alternative option studied was the one that uses 100% electricity from photovoltaic, directly from the company. This lowers electricity consumption and cuts the direct costs for utilities.

In conclusion, the innovative scenario studied can lead to many advantages for the company and the environment. The solution is not 100% satisfactory, some changes need to be made especially in the leaching process and purification treatment of the wastewater used in the precipitation of the salt. The final char output has no use nowadays, but it has potential for the future, the composition is promising and maybe it could be used in the formation of concrete, unfortunately, is still hazardous and needs to be landfilled. However, one of the most critical aspects is the percentage of avoided products. If the percentage of avoided products is not above 50% but close to 25% there is no certainty about the competitivity of this scenario with the traditional one, and maybe the economic investment could be more difficult to exploit.

The research is still ongoing and the solution to those problems is investigating.

Annex

Impact category	**Unit**	**Total**	**Methane for thermal oxidizer**	**Water to treatment**	**HCl, first leaching**	**H_2SO_4, second leaching**	**H_2O_2, second leaching**	**$Ca(OH)_2$ (lime hydrated)**	**NaOH, precipitation after the second leaching**	**Electrcity mix for the whole plant**	**Electricity from photovoltaic**	**$AlCl_3$, first precipitate. Avoided Product**	**$CuSO_4$, second precipitate. Avoided Product.**	**Wastewater treatment**	**Char residue**	**$AlCl_3$, product to waste**	**$CuSO_4$, product to waste**
Global warming	kg CO_2 eq	-510.91	15.62	0.45	2427.44	77.94	345.38	636.46	143.74	452.11	0.00	-5145.07	-1779.43	3.26	0.96	1718.35	591.87
Stratospheric ozone depletion	kg CFC11 eq	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ionizing radiation	kBq Co-60 eq	-40.15	0.07	0.20	180.65	5.58	49.85	4.12	15.98	50.36	0.00	-177.15	-344.39	0.86	0.01	59.17	114.55
Ozone formation, Human health	kg NOx eq	-8.98	0.02	0.00	5.42	0.38	0.44	0.48	0.36	0.74	0.00	-12.52	-12.75	0.02	0.01	4.18	4.24
Fine particulate matter formation	kg PM2.5 eq	-5.98	0.01	0.00	5.17	0.86	0.30	0.23	0.31	0.45	0.00	-10.25	-9.75	0.01	0.00	3.42	3.24
Ozone formation, Terrestrial ecosystems	kg NOx eq	-8.98	0.03	0.00	5.42	0.38	0.45	0.48	0.36	0.75	0.00	-12.54	-12.76	0.02	0.01	4.19	4.24
Terrestrial acidification	kg SO_2 eq	-16.65	0.04	0.00	7.95	2.79	0.82	0.60	0.51	1.38	0.00	-21.67	-24.51	0.05	0.01	7.24	8.15
Freshwater eutrophication	kg P eq	-5.46	0.00	0.00	1.06	0.09	0.19	0.03	0.07	0.13	0.00	-2.10	-8.60	0.04	0.06	0.70	2.86
Marine eutrophication	kg N eq	-0.01	0.00	0.00	0.10	0.00	0.02	0.00	0.01	0.01	0.00	-0.14	-0.26	0.11	0.00	0.05	0.09
Terrestrial ecotoxicity	kg 1,4-DCB	-34577.47	0.59	0.51	2103.49	1883.03	337.10	1189.92	197.71	252.07	0.00	-3152.54	-57606.32	2.21	0.96	1052.89	19160.90
Freshwater ecotoxicity	kg 1,4-DCB	-4537.16	0.01	0.01	32.41	57.56	14.36	0.50	2.14	5.47	0.00	-99.90	-6879.60	0.30	7.95	33.36	2288.28
Marine ecotoxicity	kg 1,4-DCB	-5636.77	0.02	0.02	45.60	74.03	19.27	1.44	3.03	7.51	0.00	-141.68	-8548.23	0.40	11.20	47.32	2843.30
Human carcinogenic toxicity	kg 1,4-DCB	-771.56	0.02	0.04	78.51	16.90	50.47	1.50	4.96	7.75	0.00	-833.72	-671.91	1.03	70.94	278.45	223.49
Human non-carcinogenic toxicity	kg 1,4-DCB	-54054.19	0.48	0.56	1563.78	1001.35	362.37	40.00	102.52	216.18	0.01	-4195.99	-82488.80	47.50	457.22	1401.38	27437.26
Land use	m^{2}a crop eq	-735.54	0.03	0.07	35.98	11.05	20.43	1.42	4.10	95.35	0.00	-53.14	-1301.67	0.31	-0.17	17.75	432.96
Mineral resource scarcity	kg Cu eq	-232.45	0.00	0.00	0.52	3.41	0.43	0.01	0.04	0.12	0.00	-47.85	-307.34	0.00	0.00	15.98	102.23
Fossil resource scarcity	kg oil eq	-11.50	25.22	0.13	647.03	46.81	124.62	62.95	35.75	141.45	0.00	-1127.23	-517.71	0.53	0.28	376.47	172.20
Water consumption	m^3	8.46	0.00	1.85	48.57	7.20	24.66	0.54	4.03	8.83	0.00	-46.01	-60.07	-16.50	0.00	15.37	19.98

Annex 1 ReCiPe midpoint - 75:25 Innovative Scenario

Impact category	**Unit**	**Total**	**Methane for thermal oxidizer**	**Water to treatment**	**HCl, first leaching**	**H_2SO_4, second leaching**	**H_2O_2, second leaching**	**$Ca(OH)_2$ (lime hydrated)**	**NaOH, precipitation after the second leaching**	**Electrcity mix for the whole plant**	**Electricity from photovoltaic**	**$AlCl_3$, first precipitate. Avoided Product**	**$CuSO_4$, second precipitate. Avoided Product.**	**Wastewater treatment**	**Char residue**	**$AlCl_3$, product to waste**	**$CuSO_4$, product to waste**
Global warming	kg CO_2 eq	4086.57	15.62	0.45	2427.44	61.14	345.38	636.46	143.74	452.11	0.00	-3431.71	-1183.74	3.26	0.96	3431.71	1183.74
Stratospheric ozone depletion	kg CFC11 eq	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ionizing radiation	kBq Co-60 eq	306.10	0.07	0.20	180.65	4.00	49.85	4.12	15.98	50.36	0.00	-118.16	-229.10	0.86	0.01	118.16	229.10
Ozone formation, Human health	kg NOx eq	7.81	0.02	0.00	5.42	0.33	0.44	0.48	0.36	0.74	0.00	-8.35	-8.48	0.02	0.01	8.35	8.48
Fine particulate matter formation	kg PM2.5 eq	7.32	0.01	0.00	5.17	0.83	0.30	0.23	0.31	0.45	0.00	-6.84	-6.49	0.01	0.00	6.84	6.49
Ozone formation, Terrestrial ecosystems	kg NOx eq	7.83	0.03	0.00	5.42	0.33	0.45	0.48	0.36	0.75	0.00	-8.36	-8.49	0.02	0.01	8.36	8.49
Terrestrial acidification	kg SO_2 eq	14.06	0.04	0.00	7.95	2.72	0.82	0.60	0.51	1.38	0.00	-14.45	-16.31	0.05	0.01	14.45	16.31
Freshwater eutrophication	kg P eq	1.66	0.00	0.00	1.06	0.07	0.19	0.03	0.07	0.13	0.00	-1.40	-5.72	0.04	0.06	1.40	5.72
Marine eutrophication	kg N eq	0.26	0.00	0.00	0.10	0.00	0.02	0.00	0.01	0.01	0.00	-0.09	-0.17	0.11	0.00	0.09	0.17
Terrestrial ecotoxicity	kg 1,4-DCB	5855.52	0.59	0.51	2103.49	1770.95	337.10	1189.92	197.71	252.07	0.00	-2102.71	-38321.80	2.21	0.96	2102.71	38321.80
Freshwater ecotoxicity	kg 1,4-DCB	114.01	0.01	0.01	32.41	50.86	14.36	0.50	2.14	5.47	0.00	-66.63	-4576.56	0.30	7.95	66.63	4576.56
Marine ecotoxicity	kg 1,4-DCB	154.05	0.02	0.02	45.60	65.55	19.27	1.44	3.03	7.51	0.00	-94.50	-5686.59	0.40	11.20	94.50	5686.59
Human carcinogenic toxicity	kg 1,4-DCB	222.67	0.02	0.04	78.51	7.45	50.47	1.50	4.96	7.75	0.00	-556.08	-446.98	1.03	70.94	556.08	446.98
Human non-carcinogenic toxicity	kg 1,4-DCB	3703.89	0.48	0.56	1563.78	913.27	362.37	40.00	102.52	216.18	0.01	-2798.68	-54874.53	47.50	457.22	2798.68	54874.53
Land use	m^2a crop eq	161.72	0.03	0.07	35.98	4.21	20.43	1.42	4.10	95.35	0.00	-35.44	-865.92	0.31	-0.17	35.44	865.92
Mineral resource scarcity	kg Cu eq	4.03	0.00	0.00	0.52	2.90	0.43	0.01	0.04	0.12	0.00	-31.91	-204.45	0.00	0.00	31.91	204.45
Fossil resource scarcity	kg oil eq	1080.24	25.22	0.13	647.03	42.30	124.62	62.95	35.75	141.45	0.00	-751.85	-344.40	0.53	0.28	751.85	344.40
Water consumption	m^3	79.01	0.00	1.85	48.57	7.01	24.66	0.54	4.03	8.83	0.00	-30.69	-39.96	-16.50	0.00	30.69	39.96

Annex 2 ReCiPe midpoint - 50:50 Innovative Scenario.

Impact category	**Unit**	**Total**	**Methane for thermal oxidizer**	**Water to treatment**	**HCl, first leaching**	**H_2SO_4, second leaching**	**H_2O_2, second leaching**	**$Ca(OH)_2$ (lime hydrated)**	**NaOH, precipitation after the second leaching**	**Electrcity mix for the whole plant**	**Electricity from photovoltaic**	**$AlCl_3$, first precipitate. Avoided Product**	**$CuSO_4$, second precipitate. Avoided Product.**	**Wastewater treatment**	**Char residue**	**$AlCl_3$, product to waste**	**$CuSO_4$, product to waste**
Global warming	kg CO_2 eq	8700.85	15.62	0.45	2427.44	61.14	345.38	636.46	143.74	452.11	0.00	-1718.35	-591.87	3.26	0.96	5145.07	1779.43
Stratospheric ozone depletion	kg CFC11 eq	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ionizing radiation	kBq Co-60 eq	653.92	0.07	0.20	180.65	4.00	49.85	4.12	15.98	50.36	0.00	-59.17	-114.55	0.86	0.01	177.15	344.39
Ozone formation, Human health	kg NOx eq	24.66	0.02	0.00	5.42	0.33	0.44	0.48	0.36	0.74	0.00	-4.18	-4.24	0.02	0.01	12.52	12.75
Fine particulate matter formation	kg PM2.5 eq	20.66	0.01	0.00	5.17	0.83	0.30	0.23	0.31	0.45	0.00	-3.42	-3.24	0.01	0.00	10.25	9.75
Ozone formation, Terrestrial ecosystems	kg NOx eq	24.70	0.03	0.00	5.42	0.33	0.45	0.48	0.36	0.75	0.00	-4.19	-4.24	0.02	0.01	12.54	12.76
Terrestrial acidification	kg SO_2 eq	44.86	0.04	0.00	7.95	2.72	0.82	0.60	0.51	1.38	0.00	-7.24	-8.15	0.05	0.01	21.67	24.51
Freshwater eutrophication	kg P eq	8.79	0.00	0.00	1.06	0.07	0.19	0.03	0.07	0.13	0.00	-0.70	-2.86	0.04	0.06	2.10	8.60
Marine eutrophication	kg N eq	0.52	0.00	0.00	0.10	0.00	0.02	0.00	0.01	0.01	0.00	-0.05	-0.09	0.11	0.00	0.14	0.26
Terrestrial ecotoxicity	kg 1,4-DCB	46400.59	0.59	0.51	2103.49	1770.95	337.10	1189.92	197.71	252.07	0.00	-1052.89	-19160.90	2.21	0.96	3152.54	57606.32
Freshwater ecotoxicity	kg 1,4-DCB	4771.87	0.01	0.01	32.41	50.86	14.36	0.50	2.14	5.47	0.00	-33.36	-2288.28	0.30	7.95	99.90	6879.60
Marine ecotoxicity	kg 1,4-DCB	5953.34	0.02	0.02	45.60	65.55	19.27	1.44	3.03	7.51	0.00	-47.32	-2843.30	0.40	11.20	141.68	8548.23
Human carcinogenic toxicity	kg 1,4-DCB	1226.37	0.02	0.04	78.51	7.45	50.47	1.50	4.96	7.75	0.00	-278.45	-223.49	1.03	70.94	833.72	671.91
Human non-carcinogenic toxicity	kg 1,4-DCB	61550.04	0.48	0.56	1563.78	913.27	362.37	40.00	102.52	216.18	0.01	-1401.38	-27437.26	47.50	457.22	4195.99	82488.80
Land use	m^{2}a crop eq	1065.82	0.03	0.07	35.98	4.21	20.43	1.42	4.10	95.35	0.00	-17.75	-432.96	0.31	-0.17	53.14	1301.67
Mineral resource scarcity	kg Cu eq	241.01	0.00	0.00	0.52	2.90	0.43	0.01	0.04	0.12	0.00	-15.98	-102.23	0.00	0.00	47.85	307.34
Fossil resource scarcity	kg oil eq	2176.51	25.22	0.13	647.03	42.30	124.62	62.95	35.75	141.45	0.00	-376.47	-172.20	0.53	0.28	1127.23	517.71
Water consumption	m^3	149.74	0.00	1.85	48.57	7.01	24.66	0.54	4.03	8.83	0.00	-15.37	-19.98	-16.50	0.00	46.01	60.07

Annex 3 ReCiPe midpoint – 25:75 Innovative scenario

Impact category	**Unit**	**Total**	**Methane for thermal oxidizer**	**Water to treatment**	**HCl, first leaching**	**H_2SO_4, second leaching**	**H_2O_2, second leaching**	**$Ca(OH)_2$ (lime hydrated)**	**NaOH, precipitation after the second leaching**	**Electricity from photovoltaic**	**AlCl3, first precipitate. Avoided Product**	**$CuSO_4$, second precipitate. Avoided Product.**	**Wastewater treatment**	**Char residue**	**$AlCl_3$, product to waste**	**$CuSO_4$, product to waste**
Global warming	kg CO_2 eq	-963.02	15.62	0.45	2427.44	77.94	345.38	636.46	143.74	0.00	-5145.07	-1779.43	3.26	0.96	1718.35	591.87
Stratospheric ozone depletion	kg CFC11 eq	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ionizing radiation	kBq Co-60 eq	-90.51	0.07	0.20	180.65	5.58	49.85	4.12	15.98	0.00	-177.15	-344.39	0.86	0.01	59.17	114.55
Ozone formation, Human health	kg NOx eq	-9.72	0.02	0.00	5.42	0.38	0.44	0.48	0.36	0.00	-12.52	-12.75	0.02	0.01	4.18	4.24
Fine particulate matter formation	kg PM2.5 eq	-6.43	0.01	0.00	5.17	0.86	0.30	0.23	0.31	0.00	-10.25	-9.75	0.01	0.00	3.42	3.24
Ozone formation, Terrestrial ecosystems	kg NOx eq	-9.73	0.03	0.00	5.42	0.38	0.45	0.48	0.36	0.00	-12.54	-12.76	0.02	0.01	4.19	4.24
Terrestrial acidification	kg SO_2 eq	-18.03	0.04	0.00	7.95	2.79	0.82	0.60	0.51	0.00	-21.67	-24.51	0.05	0.01	7.24	8.15
Freshwater eutrophication	kg P eq	-5.59	0.00	0.00	1.06	0.09	0.19	0.03	0.07	0.00	-2.10	-8.60	0.04	0.06	0.70	2.86
Marine eutrophication	kg N eq	-0.02	0.00	0.00	0.10	0.00	0.02	0.00	0.01	0.00	-0.14	-0.26	0.11	0.00	0.05	0.09
Terrestrial ecotoxicity	kg 1,4-DCB	-34829.54	0.59	0.51	2103.49	1883.03	337.10	1189.92	197.71	0.00	-3152.54	-57606.32	2.21	0.96	1052.89	19160.90
Freshwater ecotoxicity	kg 1,4-DCB	-4542.63	0.01	0.01	32.41	57.56	14.36	0.50	2.14	0.00	-99.90	-6879.60	0.30	7.95	33.36	2288.28
Marine ecotoxicity	kg 1,4-DCB	-5644.28	0.02	0.02	45.60	74.03	19.27	1.44	3.03	0.00	-141.68	-8548.23	0.40	11.20	47.32	2843.30
Human carcinogenic toxicity	kg 1,4-DCB	-779.31	0.02	0.04	78.51	16.90	50.47	1.50	4.96	0.00	-833.72	-671.91	1.03	70.94	278.45	223.49
Human non-carcinogenic toxicity	kg 1,4-DCB	-54270.35	0.48	0.56	1563.78	1001.35	362.37	40.00	102.52	0.02	-4195.99	-82488.80	47.50	457.22	1401.38	27437.26
Land use	m^2a crop eq	-830.89	0.03	0.07	35.98	11.05	20.43	1.42	4.10	0.00	-53.14	-1301.67	0.31	-0.17	17.75	432.96
Mineral resource scarcity	kg Cu eq	-232.57	0.00	0.00	0.52	3.41	0.43	0.01	0.04	0.00	-47.85	-307.34	0.00	0.00	15.98	102.23
Fossil resource scarcity	kg oil eq	-152.95	25.22	0.13	647.03	46.81	124.62	62.95	35.75	0.00	-1127.23	-517.71	0.53	0.28	376.47	172.20
Water consumption	m^3	-0.37	0.00	1.85	48.57	7.20	24.66	0.54	4.03	0.00	-46.01	-60.07	-16.50	0.00	15.37	19.98

Annex 4 ReCiPe midpoint – 25:75 Innovative scenario

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