ISSN: 2785-2997

Available online at www.HEFJournal.org

Journal of
Human, Earth, and Future

Vol. 4, No. 3, September, 2023

# Evaluating Environmental Impacts with LCA to Achieve Carbon Neutral Societies

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Received 13 May 2023; Revised 30 July 2023; Accepted 06 August 2023; Published 01 September 2023

**Abstract**

This study investigated the Life Cycle Assessment (LCA) of a manufacturing SME engaged in the metal processing industry. According to recent public tenders, LCA has a large influence in deciding whether to support a project. Even when the project describes only a part of the company's operations, LCA is mandatory. The impact of the advanced way of storing industrial gases and the inclusion of new technological equipment on environmental indicators was discussed. Input data was obtained from the company's management and the technical specifications of the new equipment. The LCA calculation was performed in the SimaPro software environment and in the ECOINVENT 3.8 database. The goal of this study was to show a positive impact of LCA even in the case of minor interventions by companies in their production processes, which do not include a comprehensive review of the company. The established practice of analyzing the life cycle of processes for the entire company represents, in the case of minor adaptations of processes, a non-rational treatment of factors that do not affect the improvement of environmental indicators. Carrying out more narrowly focused LCAs brings important information to the company about the rational inclusion of certain optional solutions at each production unit. In this way, the environmental aspect of the project is already included in the planning phase and does therefore not represent subsequently adopted decisions, which are taken simply to achieve the required standards in environmental areas. To help address these gaps, a sensitivity analysis is made on the influential input parameters, and their impact on the environmental parameters is shown. We compared the results before the company's investment (year x) and after the company's investment (year $x_1$). The results show a great positive impact on the reduction of environmental indicators and confirm the applicability of LCA in companies that tend to improve them and achieve a carbon-neutral society.

*Keywords:* Green Transition; Carbon Neutral Society; LCA; Environmental Indicators.

## 1. Introduction

The purpose of the study is to demonstrate the calculation methodology and evaluate the environmental impacts resulting from the Life Cycle Assessment (LCA) [1–3]. In the studied case, this included a review of the current situation and an evaluation of environmental indicators [4], while replacing the current system with a better one. Environmental indicators are as follows [5, 6]:

- Climate change - GWP 100a;

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http://dx.doi.org/10. 28991/HEF-2023-04-03-05

- Ozone depletion - ozone layer depletion (ODP steady state);
- Ionizing radiation;
- Photochemical formation of ozone;
- Particular matter;
- Toxicity to humans – non-carcinogenic;
- Toxicity to humans – carcinogenic;
- Acidification (including fate, average Europe total, A&B);
- Eutrophication of water resources;
- Eutrophication of freshwater sources;
- Eutrophication of the sea;
- Terrestrial eutrophication;
- Freshwater ecotoxicity;
- Land use;
- Water use;
- Use of resources, minerals and metals.

We argue that a completed LCA for individual parts of the technological plant covered by the investment significantly helps any company improve its environmental indicators. Furthermore, the results clearly show bottlenecks or areas where environmental indicators need to be improved.

LCA can be used to determine the potential impacts of a process on the environment [7, 8]. The benefit of carrying out LCA already at the project planning stage by including only the production units in question helps the company achieve the required environmental standards without additional cost but as part of planning a comprehensive project. In this way, LCA does not represent a "necessary evil" when upgrading production capacities, as most investors imagine. This method makes every intervention of the company more rational by including optimized parameters that affect environmental indicators [9, 10]. While LCA has enjoyed decades of increasing popularity as the analytic tool of choice when evaluating the systemic environmental consequences of products, materials, and industrial actions, it has yet to resolve a fundamental tension between its application as a descriptive scientific instrument and its potential as a prescriptive aid for decision-making and management. This is partly because standardized LCA methods, codified in popular software packages and ISO guidance documents, generate results that may encourage misconception, indecision, inaction, and irrelevance in comparative decision problems [11, 12].

Carrying out LCA and planning the future based on the obtained results can significantly improve our living environment. The areas covered by LCA are wide-ranging and also affect the quality of life and the general growth or decline of various populations [13–16]. The only solution for achieving the set goals of the European Green Deal [17] is performing LCA in all production activities and taking into account the actual results in further eliminating environmentally harmful factors [18]. In the present case, a different approach to investors and performing LCA for systems that are actually the subject of the company's investment in question is applied.

## 2. Method

LCA was produced using the following methodologies in accordance with standards ISO 14040 and 14044 [2, 3]:

- Defining the goal and scope;
- Inventory analysis (LCI);
- Life cycle impact assessment and;
- Interpretation through iterative processes.

In this study, the structure of the analysis was adapted for the example of the operation of production processes for years x and $x_1$. Year x represents the year before the investment, while year $x_1$ represents the year after the investment. A functional unit is the operation of production processes in one year (comparison between years x and $x_1$). In this case, production processes were defined only as processes that cover the company's investment in question.

The definition of the goal and the scope define the purpose of using the analysis, describe the system boundary, and describe the functional unit of the product or system that needs to be analyzed. The scope of the analysis is defined in the objective. The scope of the analysis can be divided into several life stages. Cradle-to-gate analysis considers the impact of the processes for the production of the digital product, electricity, fuel, and additives, as well as the impact of the transportation of raw and other materials to the place of preparation of concrete. This phase is followed by door-to-door analysis, which focuses on the digital product manufacturing process itself without considering the pre-production life stages. The final life stage is represented by the door-to-grave stage, which includes the use and maintenance of the digital product and the way it is dismantled.

All three phases can be combined in LCA from cradle to grave, which holistically describes the entire life cycle of a digital product or connected system [19]. The present case describes the cradle-to-grave method, however, only dealing with the impact of the investment object on the company.

The life cycle inventory combines energy and material flows that are included within the boundaries of the studied system. Typical information in a life cycle assessment of the operation of production processes includes the type of materials (e.g., raw materials, auxiliary materials); the energy required by the process itself and/or the production of the product and equipment (e.g., electricity); and the use of equipment. Once an inventory of different ideas about potential impacts is collected, the inventory indicators are converted into a series of environmental and human health impact categories using standardized environmental impact assessment methods and tools (e.g., EF3.0, ReCiPe, CML, TRACI, etc.) and animals [5, 6]. A typical list of impact categories under LCA includes [18, 20, 21]:

- Acidification potential;
- Climate change;
- Eutrophication potential;
- Ecotoxicity potential of freshwater sediments;
- Potential for ecotoxicity of marine water sediments;
- Terrestrial ecotoxicity potential;
- Human toxicity potential;
- Influence of ionizing radiation;
- Formation of photochemical oxidants;
- Potential for abiotic depletion and;
- Ozone layer depletion potential.

Once the effects are determined, the results are interpreted in the last step of the LCA analysis [8], followed by an explanation and a conclusion. For the purposes of the LCA study, the EP 3.0 (adapted) V1.03/EP 3.0 normalization and weighting set methodology was used, which is harmonized with ISO 14040 and 14044 [2, 3]. The EP 3.0 (adapted) V1.03/EP 3.0 normalization and weighting set method is an impact assessment method adopted in the transitional phase for determining the environmental footprint as prescribed by the European Commission. It includes normalization and weighting factors. The instructions of the SimaPro software were followed for weighting the results [18, 20, 21].

The actual calculation limits used in this study are shown in Figure 1. The input factors/parameters that directly affect the economic, environmental and social impact of the process are:

- Material;
- Energy;
- Transport;
- New process equipment.

A Life Cycle Impact Assessment (LCIA) is the result of an inventory of all flows (material, energy, and emissions) used to assess the impact of each material and emission on different impact categories [4]. The flows within the SimaPro program and the ECOINVENT 3.8 database were used to calculate the environmental impact assessment. The EP 3.0 (adapted) V1.03/EP 3.0 normalization and weighting set assessment method was used to calculate the environmental impact assessment. In Figure 1, we can see the impact of environmental indicators on different areas [22].

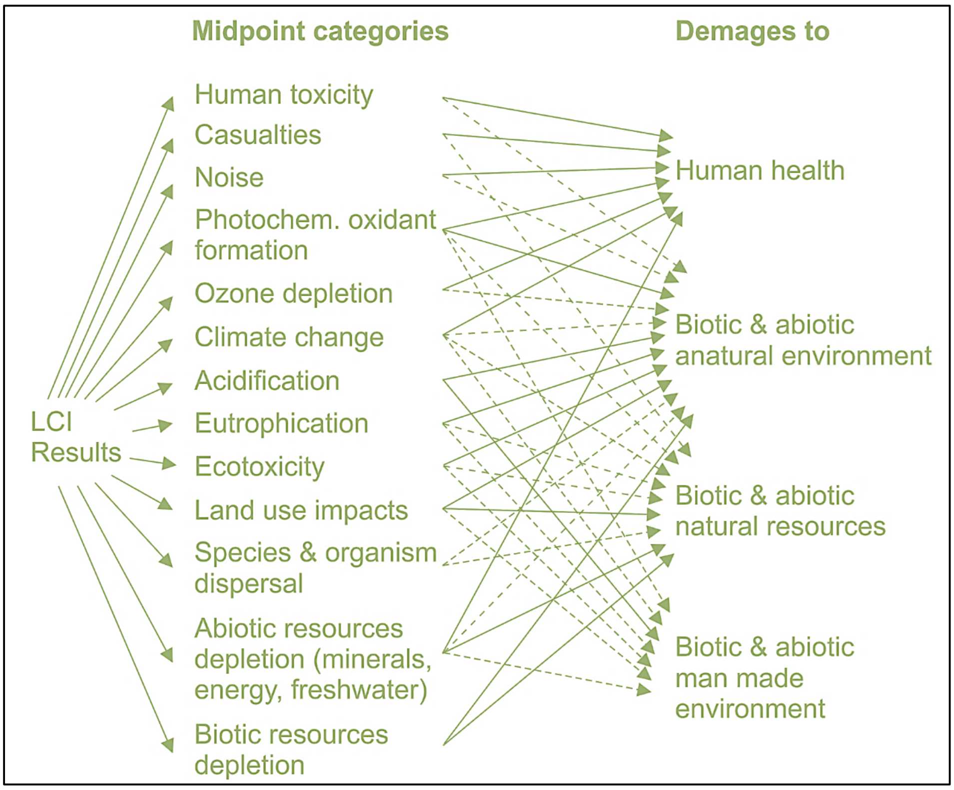

**Figure 1. Life cycle assessment framework**

***Ozone Depletion - Ozone Layer Depletion (ODP Steady State):***

Impact indicator: Impact on ozone depletion (ODP) through the evaluation of destructive effects on the stratospheric ozone layer over a 100-year time period. The concept of ozone depletion potential (ODP) was originally developed to measure the potential impact of long-lived gases, those with atmospheric lifetimes of several years, on stratospheric ozone.

***Ionizing Radiation:***

Impact indicator: The impact of ionizing radiation through the evaluation of the impact of ionizing radiation on the population compared to uranium 235.

***Photochemical Formation of Ozone:***

Impact indicator: Shows the photochemical ozone creation potential (POCP) or the impact of the potential contribution to photochemical ozone creation. It includes spatial differentiation. Considering the marginal increase in ozone formation, the spatially differentiated LOTOS-EUROS model, averaging over 14,000 grid cells, was used to define the European factors.

***Particular Matter:***

Impact indicator: Shows the incidence of diseases due to emissions of particular matter normalized per 1 kg of emitted PM2.5. The indicator is calculated using the average slope between the emission response function (ERF) operating point and the theoretical minimum risk level. The exposure model is based on archetypes that include urban environments, rural environments, and indoor environments in urban and rural areas.

***The Human Toxicity - Non-Carcinogenic:***

Impact indicator: Comparative toxic unit for human (CTUh), calculated based on the harmonized multimedia USEtox model, includes two spatial scales: a continental scale consisting of six areas (urban air, rural air, agricultural natural soil, fresh water, coastal seawater) and a global scale with the same structure but excluding urban air. Specific groups of chemicals have not yet been considered and require further evaluation.

***The Human Toxicity – Carcinogenic:***

Impact indicator: Comparative toxic unit for human (CTUh), calculated based on the harmonized multimedia USEtox model includes two spatial scales: a continental scale consisting of six compartments (urban air, rural air, agricultural natural soil, fresh water, coastal seawater) and a global scale with the same structure but without urban air. Specific groups of chemicals have not yet been considered and require further evaluation.

***Acidification (incl. Fate, Average Europe Total, A&B):***

Impact indicator: Accumulated excess values (AE) indicating the change in critical load exceedances in sensitive areas in terrestrial and freshwater ecosystems to which acidifying substances are deposited. Acidification potential refers to compounds that are precursors to acid rain. These include sulphur dioxide ($SO_2$), nitrogen oxides ($NO_x$), nitrogen monoxide (NO), nitrogen dioxide ($N_2O$) and various other substances. Acidification potential is usually indicated by $SO_2$ equivalence.

***Eutrophication of Water Resources:***

Impact indicator: Phosphorus equivalents that indicate the level at which released nutrients reach the upper limit in fresh waters at which a change in the natural cycle of nutrients begins to occur (phosphorus is considered a limiting factor in the water).

***Eutrophication of Freshwater Resources:***

Impact indicator: Phosphorus equivalents that indicate the level at which released nutrients reach the upper limit in fresh waters at which a change in the natural cycle of nutrients begins to occur (phosphorus is considered a limiting factor in surface waters).

***Sea Eutrophication:***

Impact indicator: Phosphorus equivalents that indicate the level at which released nutrients reach the upper limit in fresh waters at which a change in the natural cycle of nutrients begins to occur (phosphorus is considered a limiting factor in the sea).

***Terrestrial Eutrophication:***

Impact indicator: Accumulated excess (AE) that indicates the change in the critical load of exceeding the sensitive area on which eutrophication substances are deposited.

***Ecotoxicity for Fresh Water:***

Impact indicator: Benchmark Ecosystem Toxicity Unit (CTUe) calculated based on the harmonized multimedia USEtox model, includes two spatial scales: a continental scale consisting of six compartments (urban air, rural air, agricultural natural soil, fresh water, coastal seawater) and a global scale with the same structure but without urban air. Specific groups of chemicals require further work.

***Land Use:***

Impact indicator: Soil quality index calculated from the CF set based on the LANCA® model in 2.2. Of the 5 original indicators, only 4 were included in the aggregation (physical-chemical filtration was excluded due to high correlation with mechanical filtration).

***Water Use:***

Impact indicator: Potable water scarcity potential (water consumption weighted by scarcity). Relative Available Water Remaining per area (AWARE) is the amount of water in a given area after the needs of humans and aquatic ecosystems have been met. This indicator is only recommended for the characterization of blue water consumption, where consumption is defined as the difference between the withdrawal and discharge of blue water. Green water, fossil water, sea water and rainwater cannot be correctly labelled with this set of indicators. Not included in AWARE100: distinction between agriculture and non-agriculture at country level, temporal (monthly) specification, and characterization factors at watershed level.

***Use of Resources, Minerals and Metals:***

Impact indicator: Depletion of abiotic resources (ADP terminal stock) calculated based on correlations according to van Oers et al. [23], included in CML2016, v.4.8. The depletion model is based on the relationship between usage and availability. A possible complete replacement between fossil energy sources is envisaged. Individual regions are assigned a national characterization factor. Connected (e.g. energy) regions spanning more than one country (e.g. WECC) are assigned a GLO characterization factor.

In order to assess the effectiveness of the introduction of digital transformation, we performed a comparative analysis of the circular cycle (LCA), in which the production of a typical digital product as a reference state was summarized and compared with the predicted state after the implementation of the transformation. LCA was calculated according to the EF3.0 method using the SimaPro 9.3.0 software package and considering reference data from the EcoInvent 3.0 and Industry Data 2.0 database.

## 3. Results

### 3.1. LCA Boundary Conditions

The aim of the study is to compare the impacts on the environment and human health with current production processes (year x) and processes that will be introduced in the company's operations (year $x_1$).

LCA includes product manufacturing processes, transportation, including fuel and electricity consumption, and the proportion of process equipment used to manufacture the product.

***Functional Unit:***

The functional unit we studied included 1 year of operations of the company's production processes. We compared the years x (old state) and $x_1$ (new state).

***Limitations of the Calculated Model:***

In the LCA, the total impacts of the production of process equipment were included in the calculations in accordance with the EcoInvent 3 database. Figure 2 shows the boundaries of the studied system.

In LCA, we took into account that the existing waste material after the investment in year $x_1$ is partially used as input material. This is made possible by better technological parameters of the new equipment. In this case, the waste material was treated in a similar way as already described in the article *Waste is not a service* [24].

**Figure 2. Calculation boundaries**

### 3.2. Uncertainty Analysis

To determine the overall uncertainty of the LCA results, an uncertainty analysis was performed through sampling-based Monte Carlo simulations [25]. The basic calculation for the functional unit was made on the obtained data provided by the company. For the purpose of LCA, the data was consistently considered when calculating the environmental footprint for the functional unit, whereby the data on individual material, process, operations, energy use and process equipment was summarized according to the EcoInvent 3 database. Only the effects of the actual investment that the company is deciding on were discussed.

The impact of the advanced way of storing industrial gases, the inclusion of a robotic welding cell, the integration of an air filtration system and a central emulsion preparation system on environmental indicators was discussed. The advanced way of storing industrial gases involves replacement of the classic storage of industrial gases in cylinders with pipe distribution for gases throughout all production rooms and central tanks of industrial gases. With the current use of gas cylinders, 10% of the gas volume remains in each cylinder. With the new pipe distribution there will be no losses or leftovers. With this, the company will contribute to the reduction of gas transport in cylinders (mixtures, argon, acetylene, nitrogen, oxygen).

The pipe distribution for gases with a central tank enables the use of a central tank for storing industrial gases (mixture of oxygen and acetylene and natural gas). By using natural gas to preheat semi-finished products before welding, the company will replace the usage of a mixture of oxygen and acetylene, which is more dangerous to the environment, compared to natural gas. This will replace approximately 15% of the oxygen-acetylene mixture used in year x. The pipeline distribution for gases with a central tank significantly reduces the intensity of transport (delivery will take place in larger quantities and at longer intervals).

*Current state of transport*: 3 weekly trucks: 57.2 km.

*Transport status after transformation*: 2 monthly trucks: 57.2 km.

**Figure 3. Distance for transporting industrial gas cylinders**

Gas, consumed in year x:

- Mixtures, argon, acetylene, nitrogen, oxygen (cutting, welding, preheating): 81,125.4 kg.
  - By installing a gas pipeline and adjusting the pressure system, the gas used for preheating (15% mixture of acetylene and oxygen) will be replaced with natural gas.
- Natural gas (heating, pre-heating): 2,345 kg.
  - The consumption in year $x_1$ will increase at the expense of a decrease in the consumption of the mixture of acetylene and oxygen (preheating).

It is planned that the amount of acetylene-oxygen mixture used for preheating the material will be replaced by natural gas in year x1. This represents 15% of the consumed volume of mixtures, which means 7,412.80 kg more consumption of natural gas. The transition to the use of another type of gas will enable a new system for gas distribution throughout the production premises.

$$\begin{aligned} &Increased\ consumption\ of\ natural\ gas \\ &\quad = (Consumption\ of\ oxygen\ mixture\ per\ acetylene\ in\ year\ x \\ &\quad - reduction\ of\ consumption\ of\ oxygen\ and\ acetylene\ mixture) \cdot 0.15 \\ &\quad = (54{,}910\ kg - 54{,}910\ kg \cdot 0.1) \cdot 0.15 = 7{,}412.80\ kg \end{aligned}$$

$$Consumption\ of\ the\ mixture\ of\ oxygene\ and\ acetylene\ in\ the\ year\ x = 7{,}436\ kg + 26{,}241.6\ kg + 21{,}232\ kg = 54{,}910\ kg$$

$$\begin{aligned} &Natural\ gas\ consumption\ in\ year\ x_1 = Natural\ gas\ consumption\ in\ year\ x + Increased\ natural\ gas\ consumption \\ &\quad = 2{,}345\ kg + 7{,}412.80\ kg = 9{,}757.80\ kg \end{aligned}$$

**Table 1. Gas consumption for the production process operations for the years x and x1 of the company**

| Gas | Gas Consumption (kg) | |
|---|---|---|
| | Year x | Year $x_1$ |
| Oxygen cylinder 40/150 | 7,436 | 5,688.54 (-10%; -15%)[*] |
| Oxygen 3.5 battery 12x50/200 | 26,241.6 | 20,074.82 (-10%; - 15%)[†] |
| Acetylene, dissolved, 2, II, ADR | 21,232 | 16,242.48 (-10%; -15%)[‡] |
| Enermix mix C18 cylinder 50/200 | 24,480.4 | 22,032.36 (-10%) |
| Enermix mix C3 cylinder 50/200 | 58.8 | 52.92 (-10%) |
| Enermix mix C18 cylinder 50/200 battery | 764.4 | 687.96 (-10%) |
| Argon cylinder 50/200 | 756 | 680.4 (-10%) |
| Nitrogen 5.0 cylinder 50/200 | 156.2 | 140.58 (-10%) |
| TOTAL mixtures, argon, acetylene, nitrogen, oxygen (cutting, welding, preheating) | 81,125.4 | 73,012.86 |
| Natural gas | 2,345<br>(500 heating, 1,845 cooling) | 9,757.80 |
| **Transport** | **km** | |
| | 716,176.03 tkm | 170,441.33 tkm |

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[*] $= (7{,}436\ kg - 7{,}436\ kg \cdot 0.1) \cdot 0.85$

[†] $= (26{,}241.6\ kg - 26{,}241.6\ kg \cdot 0.1) \cdot 0.85$

[‡] $= (21{,}232\ kg - 21{,}232\ kg \cdot 0.1) \cdot 0.85$

*Transport in the year x:* 3x weekly, 57.2 km each

*Transport in the year $x_1$:* 2x monthly, 57.2 km each

For the calculation, we consider that an average year has 50 working weeks.

$\text{Distance travelled in the year x} = 3 \cdot 50 \cdot 57.2\ km = 8{,}580\ km$

$\text{Amount of gasses, transported in the year x} = 81{,}125.4\ kg + 2{,}345\ kg = 83{,}470.4\ kg$

81,125.4 kg represents the amount of gases used for cutting, welding and preheating, while 2.345 kg represents the amount of natural gas.

$\text{Distance travelled in the year } x_1 = 2 \cdot 12 \cdot 57.2\ km = 2{,}059.2\ km$

$\text{Amount of gasses, transported in the year } x_1 = 73{,}012.86\ kg + 9{,}757.80\ kg = 82{,}770.66\ kg$

73,012.86 kg represents the amount of gases used for cutting, welding and preheating, while 9,757.80 kg represents the amount of natural gas.

*Year x:* $8{,}580\ km \cdot 83.4704\ t = 716{,}176.03$ tkm

*Year $x_1$:* $2{,}059.2\ km \cdot 82{,}770.66\ t = 170{,}441.34$ tkm

A comparison of the results for year x and year $x_1$ clearly shows a significant reduction in gas consumption depending on the distance covered for gas transport: The reduction is 76.2%. Evaluating transport with the assessment of environmental impacts of city roads is based on the example described in the article *Life cycle assessment (LCA) to evaluate the environmental impacts of urban roads: a literature review* [26].

The second discussed issue in LCA is the replacement of classic manual welding devices with a robotic welding cell. Compared to a classic manual welding machine, the robotic welding cell uses 17% less electricity for the same product (faster welding, not as much subsequent grinding is required, less scale) and 18% less input raw materials/other material (less scale, higher efficiency of the welding wire due to larger reels and smaller reel remnants). Due to a more efficient welding, significantly less harmful fumes are released during the process.

**Table 2. Consumption of electricity and raw materials for the production process operations for the years x and $x_1$ of the company**

| | **Year x** | **Year $x_1$** |
|---|---|---|
| **Electricity consumption** | **kWh** | |
| Welding | 233,763.8 | 194,024 (-17%) |
| **Amount of raw materials used** | **ton** | |
| Metal: sheet metal, pipes, solid steel | 1,680 | 1,377.5 (-18%) |
| **Waste** | **ton** | |
| | 2% Raw Materials = 33.6 tons | No Waste |

The data presented in the table were obtained from the company's internal records for the discussed production processes with existing equipment and technical specifications, as well as collected data from the manufacturer of the new equipment. The manufacturer's data on the new equipment is based on the collection of data on already-installed devices and feedback from previous customers.

The air filtration system will clean the air of harmful fumes produced during welding. Extraction hoods are installed right above the welding place so that the spread of flue gases on the production premises is prevented. The filter system uses the best available energy-efficient electric motors with efficiency according to the premium efficiency IE3 standard, which are equipped with frequency converters, which affects the overall energy efficiency of the investment [27]. The reduction of energy consumption during the technological process has a crucial and wide impact on the reduction of environmental impacts. Environmental and energy issues are strictly interconnected and require a comprehensive understanding of resource management strategies and their implications [28].

The central emulsion preparation system enables the company to independently prepare the emulsion, which will be independent of external contractors. Currently, 2,700 liters of oil are used per year to prepare the emulsion. From this, they prepare 40 $m^3$ of emulsion, which results in the consumption of 37,300 L of water (mixture: 93% water, 7% oil). By purchasing a central emulsion preparation system, it will be possible to use the same emulsion for a minimum of 4 years. However, there are emulsion losses during processing processes (evaporation, runoff due to spraying). On an annual basis, the company will save 8 $m^3$ of emulsion (500 L of oil and 7,500 L of water).

Data on current emulsion consumption are obtained from the company's internal records. The emulsion consumption data with the new system are obtained from the technical specifications and calculations that are included in the basic planning of the entire system.

**Table 3. Oil and water consumption for the production process operations for the years x and $x_1$ of the company**

| | Year x | Year $x_1$ |
|---|---|---|
| **Oil** | **L** | |
| | 2,700 | 2,200 |
| **Water** | **L** | |
| Water for preparation of emulsion | 37,300 | 29,800 |

We used the data obtained from the presented calculations and the company's internal records as input parameters for LCA.

## 3.3. Outputs

The following tables show the results of the comparison of LCA impacts in absolute values and the comparison of normalized impacts calculated according to the EF 3.0 Method (adapted) V1.03 and criteria [20, 21]. Absolute and normalized total impacts are given, which are calculated within the limits given in the previous chapter and based on inventory data, also provided in the previous chapter. The tables show the difference between the production processes for years x and $x_1$ in absolute values and in%, which is calculated based on the base state (year x). Calculations considering normalized values are also presented graphically, while graphical representations are also given for comparing normalized values, shown as a total impact [8].

In accordance with the LCA standard, normalization is defined as "calculation of the range of results of category indicators according to reference information" and weighting as "transformation and possible aggregation of indicator results by impact categories using numerical factors based on value choices". All weighted results have the same unit and can be summed to create a single result for the environmental impact of a product or scenario. Simply put, weighting means applying a value judgment to LCA results [18]. Mandatory elements of the LCA are classification and characterization. Optional elements are normalization, ranking, clustering, and weighting.

This means that every LCA, according to ISO, must include at least classification and characterization. If these steps are not included, the study can only refer to the life cycle inventory (LCI). Normalization and weighting are used to simplify the interpretation of the results. These steps are considered optional steps in ISO 14040 and 14044 as they contain additional subjective steps. Normalization shows to what extent the result of the impact category indicator has a relatively high or relatively low value compared to the reference. Normalization also solves the incompatibility of units, as each influence or category has its own unit, so the results cannot be compared without normalization. Weighting is the most controversial and difficult step in life-cycle impact assessment. Weighting was the starting point for the development of the Eco-indicator 99 and ReCiPe methods, where some of the problems associated with weighting have been reduced or resolved, but the weighting step will always remain difficult [5]. An interesting approach was developed by Hofstetter et al. [19] using the weighted triangle.

All inventory data is uncertain to some extent. This data uncertainty can be described by a distribution characterized by a standard deviation. Performing LCA with uncertain data can be risky, especially when using LCA to compare two products. All the uncertainties in the various data inputs add up and can greatly affect the LCA results. In order to see the total impact of all input uncertainties, the Monte Carlo analysis was applied to calculate the uncertainty of LCA results—how much range there is in the actual results based on variable inputs [29–31].

The basis of Monte Carlo simulation is the study of the behavior of random variables in the system with the help of random number generation [29, 32]. It is intended to solve problems involving uncertainty. Problem-solving is undertaken by performing a random sampling of a set of elements, in which each element has a certain probability of being selected. Simulation can be used wherever random variables appear in the process, such as inventory management, planning, etc. In general, Monte Carlo simulation is a convenient tool for estimating the magnitude of risk, especially business risk. As a probability distribution for the foreground input values, a triangular distribution with minimum, maximum, and average values was assumed [25, 31].

A sensitivity analysis was performed to investigate how changes in selected input parameters affected the overall results. Changes were made to the gas consumption, transport distances, electricity consumption, amount of raw material, amount of waste, oil consumption, and water consumption. The best case is presented for new equipment in the year $x_1$. The worst case is presented for existing equipment in the year x.

**Table 4. Calculation of LCA criteria (absolute values) according to EF 3.0 Method (adapted) V1.03 for 1-year operations of production processes for years x and $x_1$ – comparison**

| Impact Category (Environmental Impact) | Unit | Year x | Year $x_1$ | Difference (Total value) | Difference (%) |
|---|---|---|---|---|---|
| Climate change | kg CO2 eq | 2,294,643.914 | 1,898,810.867 | 395,833.05 | 17.3 |
| Ozone depletion | kg CFC11 eq | 0.04362003 | 0.023263547 | 0.02 | 46.7 |
| Ionising radiation | kBq U-235 eq | 258,671.57 | 243,117.5094 | 15,554.06 | 6.0 |
| Photochemical ozone formation | kg NMVOC eq | 5944.525864 | 4,740.365579 | 1,204.16 | 20.3 |
| Particulate matter | disease inc. | 0.055675054 | 0.040692555 | 0.01 | 26.9 |
| Human toxicity, non-cancerous | CTUh | 0.02772841 | 0.022600176 | 0.01 | 18.5 |
| Human toxicity, cancerous | CTUh | 0.007555112 | 0.006183848 | 0.00 | 18.2 |
| Acidification | mol H+ eq | 14,908.72637 | 13,170.65206 | 1,738.07 | 11.7 |
| Eutrophication, freshwater | kg P eq | 930.2291589 | 885.8848612 | 44.34 | 4.8 |
| Eutrophication, marine | kg N eq | -4,919.004638 | -4,062.325829 | -856.68 | 17.4 |
| Eutrophication, terrestrial | mol N eq | 15,190.61709 | 11,857.38784 | 3,333.23 | 21.9 |
| Ecotoxicity, freshwater | CTUe | 7,046,361.421 | 5,452,304.051 | 1,594,057.37 | 22.6 |
| Land use | Pt | 2,494,964.097 | 1,370,678.817 | 1124285.28 | 45.1 |
| Water use | m3 depriv. | 270,936.3875 | 245,504.8971 | 25,431.49 | 9.4 |
| Resource use, fossils | MJ | 29,582,863.9 | 24,689,015.39 | 4,893,848.51 | 16.5 |
| Resource use, minerals, and metals | MJ | 233,149.3020 | 180,557.2666 | 52,592.04 | 22.6 |

**Table 5. Calculation of LCA criteria (weighted values) according to EF 3.0 Method (adapted) V1.03 for 1-year operations of production processes for years x and $x_1$ – comparison**

| Impact Category (Environmental Impact) | Unit | Year x | Year $x_1$ | Difference (Total value) | Difference (%) |
|---|---|---|---|---|---|
| **Total (Common Impact)** | **Pt** | **163.5202905** | **137.4223564** | **26.10** | **15.96** |
| Climate change | Pt | 59.68162304 | 49.38636172 | 10.30 | 17.25 |
| Ozone (layer) depletion | Pt | 0.051305181 | 0.027362212 | 0.02 | 46.67 |
| Ionising radiation | Pt | 3.071388621 | 2.886704371 | 0.18 | 6.01 |
| Photochemical ozone formation | Pt | 6.998573523 | 5.580898761 | 1.42 | 20.26 |
| Particulate matter | Pt | 8.380654586 | 6.125368935 | 2.26 | 26.91 |
| Human toxicity, non-cancerous | Pt | 2.221422751 | 1.81058145 | 0.41 | 18.49 |
| Human toxicity, cancerous | Pt | 9.522349368 | 7.794028525 | 1.73 | 18.15 |
| Acidification | Pt | 16.63813862 | 14.6984477 | 1.94 | 11.66 |
| Eutrophication, freshwater | Pt | 16.20868496 | 15.43601218 | 0.77 | 4.77 |
| Eutrophication, marine | Pt | -7.449025808 | -6.151726246 | -1.30 | 17.42 |
| Eutrophication, terrestrial | Pt | 3.188689776 | 2.489005625 | 0.70 | 21.94 |
| Ecotoxicity, freshwater | Pt | 3.169847963 | 2.452751691 | 0.72 | 22.62 |
| Land use | Pt | 0.241682182 | 0.132774916 | 0.11 | 45.06 |
| Water use | Pt | 2.010312503 | 1.821614176 | 0.19 | 9.39 |
| Resource use, fossils | Pt | 37.85470597 | 31.59245912 | 6.26 | 16.54 |
| Resource use, minerals, and metals | Pt | 1.729937279 | 1.339711229 | 0.39 | 22.56 |

The most important result in Table 5 shows the total impact of the investment or the difference arising from different values of the input parameters considered in the sensitivity analysis. The LCA result shows a 15.96% reduction in the total impact of environmental indicators. For the investor, this is decisive information for assessing the feasibility of the investment.

**Table 6. Calculation of LCA criteria (normalized values) according to EF 3.0 Method (adapted) V1.03 for 1-year operations of production processes for years x and $x_1$ – comparison**

| Impact Category (Environmental Impact) | Unit | Year x | Year $x_1$ | Difference (Total Value) | Difference (%) |
|---|---|---|---|---|---|
| Climate change | - | 283.3885234 | 234.5031421 | 48.89 | 17.25 |
| Ozone depletion | - | 0.813077358 | 0.433632522 | 0.38 | 46.67 |
| Ionising radiation | - | 61.3051621 | 57.61884973 | 3.69 | 6.01 |
| Photochemical ozone formation | - | 146.413672 | 116.7552042 | 29.66 | 20.26 |
| Particulate matter | - | 93.53409136 | 68.36349258 | 25.17 | 26.91 |
| Human toxicity, non-cancerous | - | 120.7294973 | 98.40116578 | 22.33 | 18.49 |
| Human toxicity, cancerous | - | 447.0586558 | 365.9168322 | 81.14 | 18.15 |
| Acidification | - | 268.3570746 | 237.0717371 | 31.29 | 11.66 |
| Eutrophication, freshwater | - | 578.8816056 | 551.2861491 | 27.60 | 4.77 |
| Eutrophication, marine | - | -251.6562773 | -207.8285894 | -43.83 | 17.42 |
| Eutrophication, terrestrial | - | 85.94851149 | 67.08910041 | 18.86 | 21.94 |
| Ecotoxicity, freshwater | - | 165.0962481 | 127.7474839 | 37.35 | 22.62 |
| Land use | - | 3.043856198 | 1.672228156 | 1.37 | 45.06 |
| Water use | - | 23.62294363 | 21.40557198 | 2.22 | 9.39 |
| Resource use, fossils | - | 454.9844468 | 379.7170568 | 75.27 | 16.54 |
| Resource use, minerals, and metals | - | 22.91307654 | 17.74451959 | 5.17 | 22.56 |

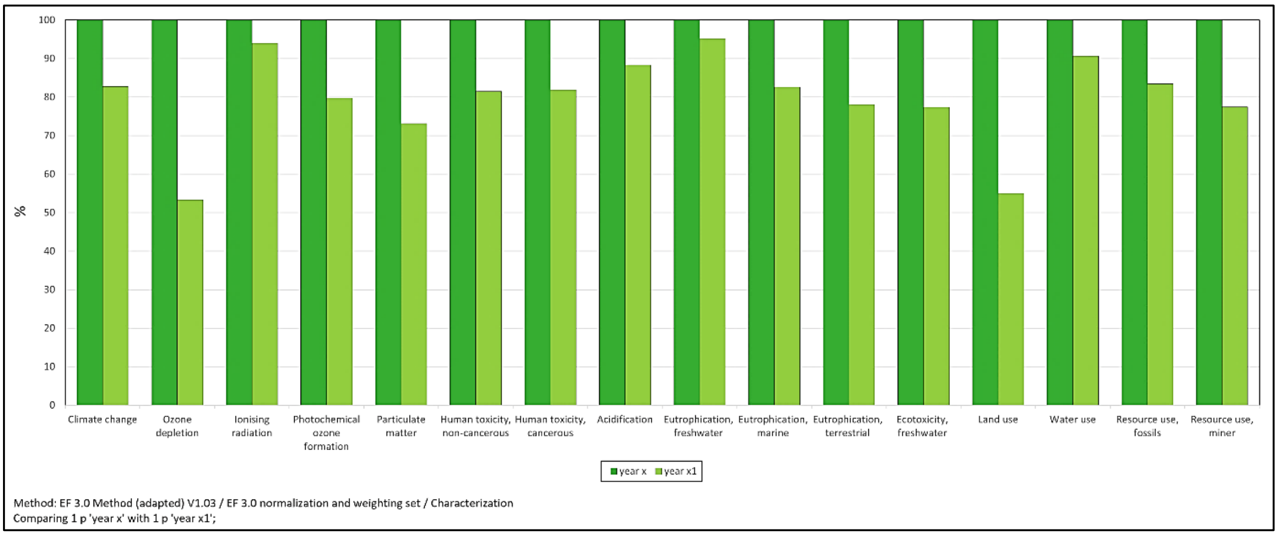


**Figure 4. Comparison of LCA impacts for 1 year of operations of production processes for years x and $x_1$ (characterization – comparison in percentages)**

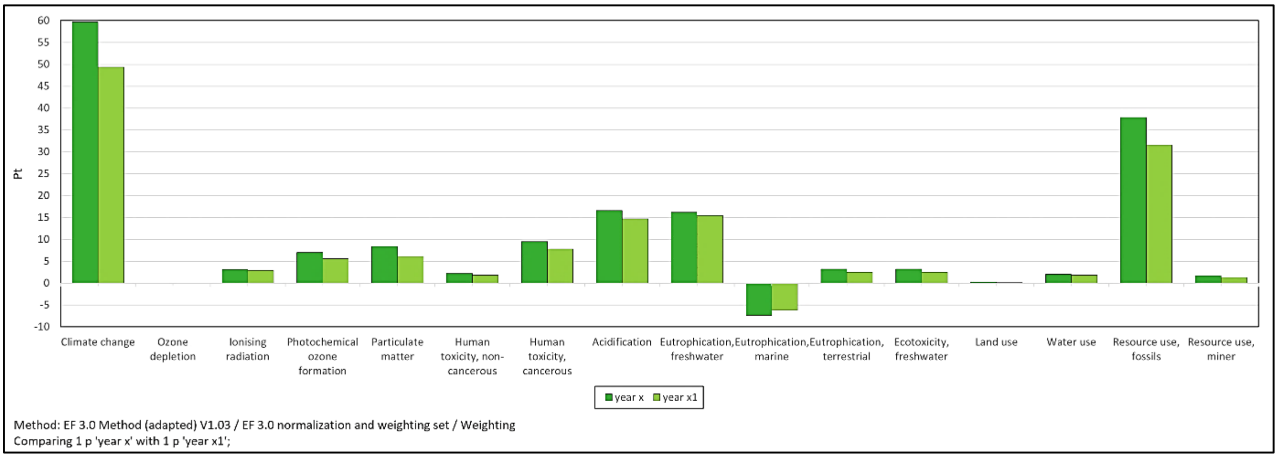
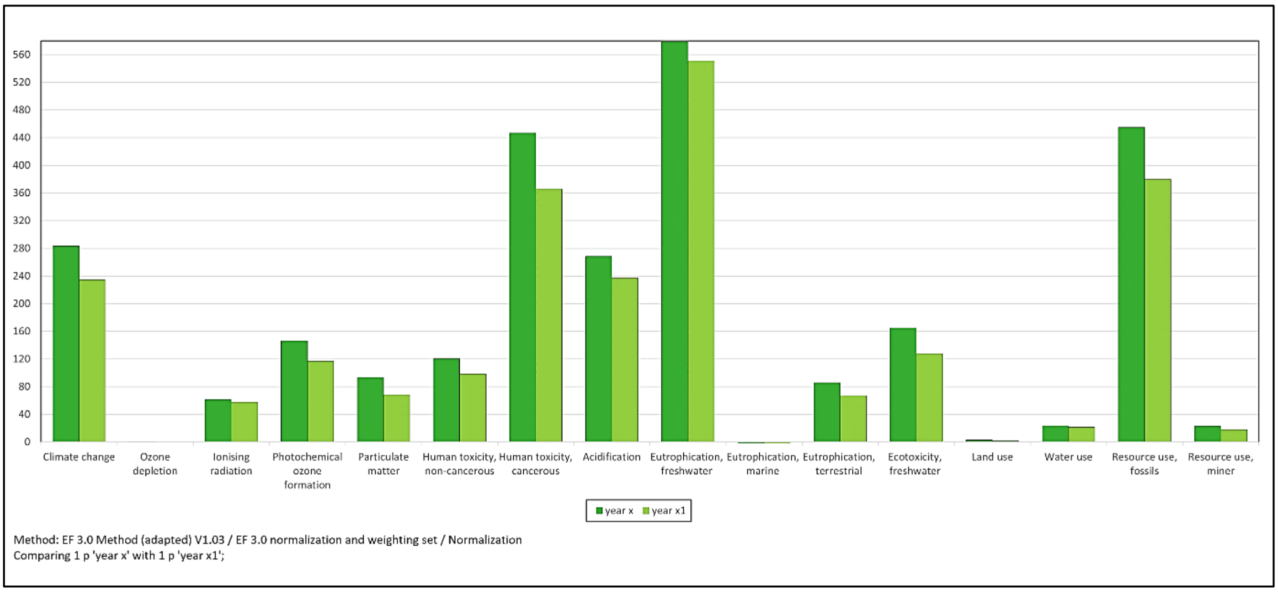
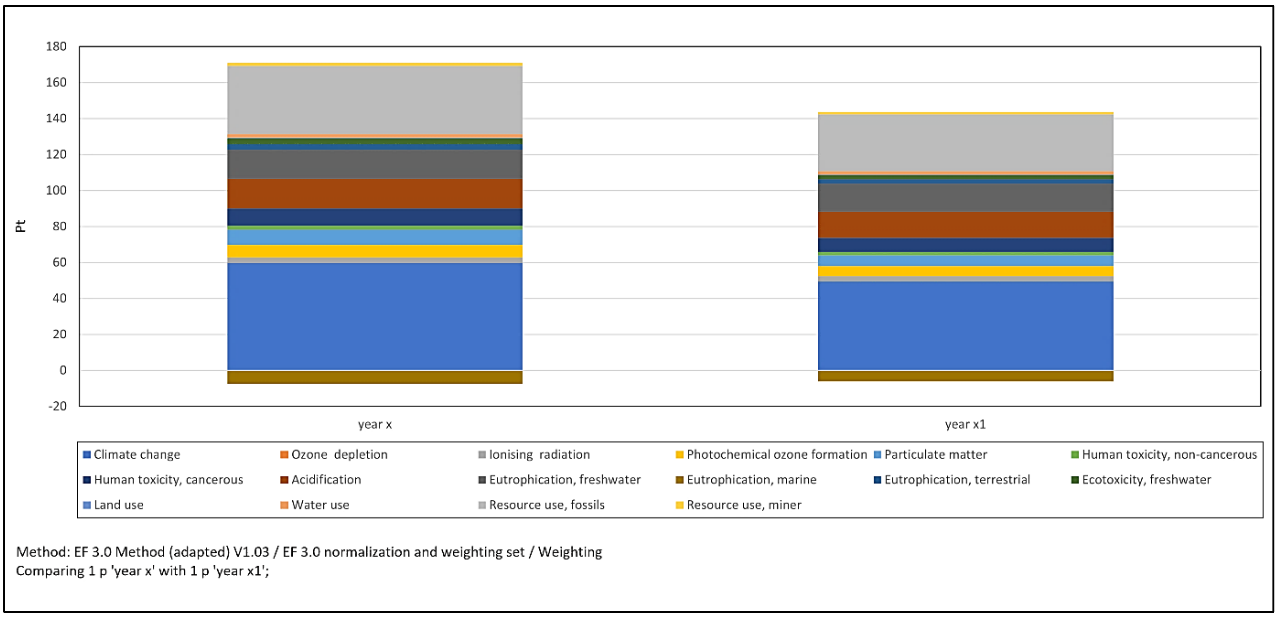


**Figure 5. Comparison of LCA impacts for 1 year of operations of production processes for years x and $x_1$ (weighted data)**



Method: EF 3.0 Method (adapted) V1.03 / EF 3.0 normalization and weighting set / Normalization
Comparing 1 p 'year x' with 1 p 'year x1';

**Figure 6. Comparison of LCA impacts for 1 year of operations of production processes for years x and $x_1$ (normalized data considering the reference state)**



Method: EF 3.0 Method (adapted) V1.03 / EF 3.0 normalization and weighting set / Weighting
Comparing 1 p 'year x' with 1 p 'year x1';

**Figure 7. Comparison of LCA impacts for 1 month operation of production processes with different transport of input material - comparison (normalized and weighted data - single score)**

### 3.4. Interdependence Tree

Figures 8 and 9 show LCA network connections (network) and LCA trees of interdependence of individual processes, which include the use of electricity, heating, transport, and other resources and processes for 1-month operation of the automatic line based on the information from Table 5. On the trees, the connections are more or less emphasized, which means that they also show the magnitude of the process in the overall LCA analysis; therefore, the thicker the line, the greater the impact the process has on the entire LCA cycle [8].

Calculation method: EP 3.0 (adapted) V1.03 / EP 3.0 normalization and weighting set.

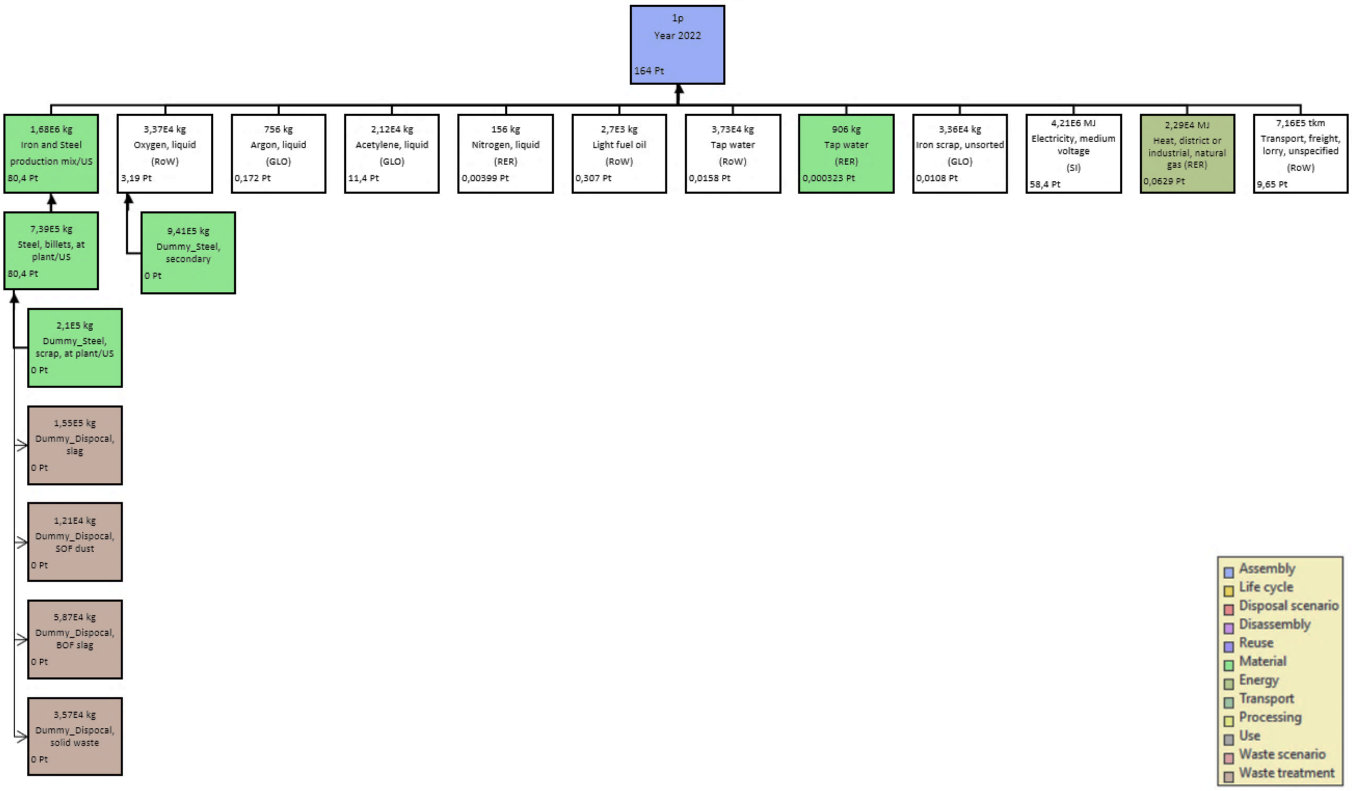


**Figure 8. LCA network connection (network) for 1 year of production operations - year x**

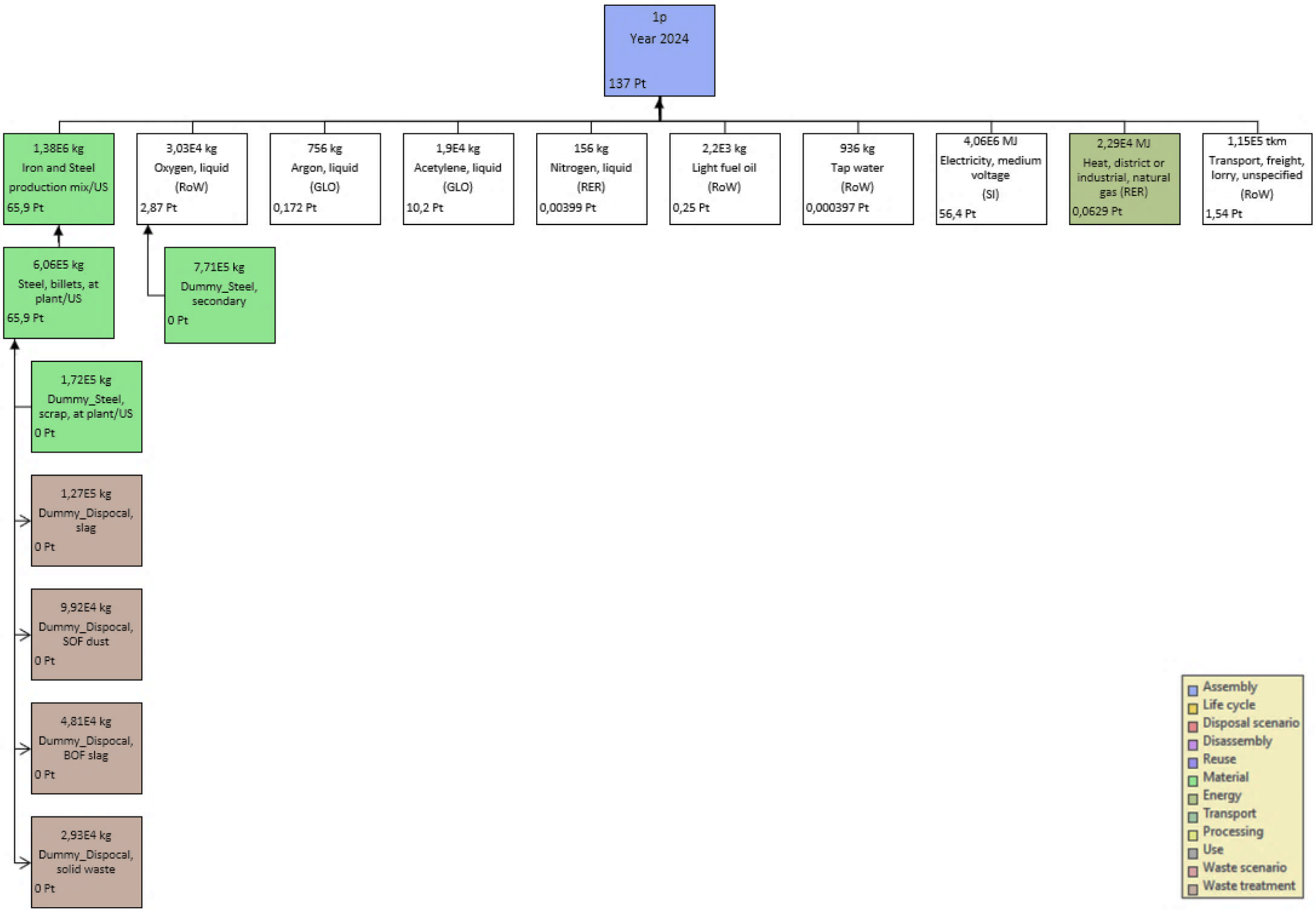


**Figure 9. LCA network connection (network) for 1 year of production operations - year $x_1$**

## 4. Discussion

From the presented results, it is clear that the new investment, which will already show results in year $x_1$, will certainly be much more environmentally favorable since the impacts on absolutely all environmental factors are lower than in year x. The difference in the total impact expressed in Pt units is around 16% (15.96%) in favor of the year $x_1$, which represents the year after the new investment or transformation in production processes.

According to the individual criteria used to evaluate the overall impact, the differences are evenly distributed in favor of year $x_1$. The biggest differences between years x and $x_1$ are noticeable in the *ozone layer depletion* and land use criteria, which means that the impact will decrease the most in these two criteria. However, the environmental impact will decrease the least in the case of the *eutrophication of freshwater sources* (approximately 4%).

Weighted data on the impact on individual climate factors show that the greatest impact is on climate change, which will decrease (17.25%) in the year $x_1$ just like other factors.

All processes and materials in the operations of production processes result in 2.29E6 kg $CO_2$ eq. (year x) and 1.9E6 kg $CO_2$ eq. (year $x_1$), where we see the difference that emissions are definitely reduced by year $x_1$ when they are introduced into production process innovations (calculated on the basis of data from the Ecoinvent 3 database for impact on climate change). The difference is 390,000 kg $CO_2$ eq., which is 17.03%.

All processes in 1-year operations are 15.96% lower in year $x_1$ (compared to year x), which means that the company will greatly reduce its environmental footprint. We observe a very large impact in reducing transport (more than 90%), and we also see a value in water consumption, but we cannot take it for granted because there is still no evidence of the consumption that will follow in year $x_1$.

The LCA analysis is intended to compare the sustainability and environmental footprint of the company's production processes and operations (x and $x_1$) over a 1-year period. It should be emphasized that the calculation for year x is much more environmentally friendly as a result, and with further measures, the company can have an even stronger impact on the reduction of environmental burdens in its development in terms of factors such as electricity consumption, heating and, above all, the consumption of input raw materials.

## 5. Conclusion

The LCA analysis examined the environmental impact or environmental burdens during the first year of operations of the production processes of a manufacturing company. We compared year x (no news) and year $x_1$ (news). Bottlenecks or room for reducing the environmental burden are mainly found in the transport of gas, the greater part of which will be lost during the transformation. The environmental impact is also greatly influenced by the consumption of electricity and the volume of raw materials. The LCA analysis represents individual processes and evaluates their impact on total environmental loads and on individual impact categories.

Carrying out LCA analyses is crucial for companies if we want to achieve a carbon-neutral society. The results are an excellent indicator of weak points in the environmental field for all types of companies and provide the best possible directions for the company to achieve better environmental indicators. Intensive performance of LCA analyses and consideration of the results in further improvement of environmental indicators will significantly speed up the movement through the green transition to a carbon-neutral society or achieving the set goals of the European Green Deal.

## 6. Declarations

### 6.1. Author Contributions

Conceptualization, M.P., L.R.M., and D.K.; methodology, D.K. and M.P.; software, D.K. and M.P.; validation, M.P. and L.R.M.; formal analysis, D.K., M.P., and L.R.M.; investigation, D.K., M.P., and L.R.M.; resources, M.P., L.R.M., and D.K.; data curation, M.P. and L.R.M.; writing—original draft preparation, D.K. and M.P.; writing—review and editing, M.P., L.R.M., and D.K.; supervision, M.P. and L.R.M.; project administration, M.P. and L.R.M.; funding acquisition, M.P. All authors have read and agreed to the published version of the manuscript.

### 6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

### 6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

### 6.4. Institutional Review Board Statement

Not applicable.

### 6.5. Informed Consent Statement

Not applicable.

### 6.6. Declaration of Competing Interest

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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