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A global approach for recovery of arable land through improved phytoremediation coupled with advanced liquid biofuel production and climate friendly copper smelting process

Deliverable D4.2: Report on Environmental Impact Assessment of Phy2Climate

for:
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N°	Short	Beneficiary	Role
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2	Fraunhofer	Fraunhofer Gesellschaft	BEN
3	AUR	Aurubis AG	BEN
4	LEITAT	LEITAT Technological Center	BEN
	CUJ	Central University of Jharkand	IL3P
5	IFVCNS	Institute of Field and Vegetable Crops	BEN
6	SUT	Silesian University of Technology	BEN
7	ETA	ETA Florence Renewable Energies	BEN
8	UHA	University Hasselt	BEN
9	INTA	National Institute of Agricultural Technology Argentina	BEN
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11	BVA	Biovala	BEN
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14	CLH	Compania Logistica de Hidrocarburos S.A.	BEN
15	PUW	Pro Umwelt	BEN
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CONTENT

1 EXECUTIVE SUMMARY

This deliverable presents the results of the first iteration of Life Cycle Assessment (LCA) of phytoremediation and biofuel production. After defining the goal and scope of the assessment, primary inventory data have been collected from four pilot phytoremediation sites and from the biorefinery and supplemented with secondary data based on literature review and our own mathematical calculations. The data have been then fed into a LCA model of pilot sites and biorefinery prepared in *LCA for Experts* software. Environmental impacts have been calculated using Environmental Footprint 3.1 methodology.

Conducting a LCA is an iterative multi-step process. The first step is a definition of the goal and the scope. The goal of LCA is to evaluate the sustainability of Phy2Climate technology. Proving the environmental-friendly and sustainable nature of the proposed technology is pivotal in overcoming possible social and legal barriers and facilitating the commercialization of technology. The investigated technology consists of two subsystems which can operate independently: phytoremediation and biorefinery. These subsystems have been first assessed separately (using different functional units), and afterwards an assessment of the combined process has been carried out. The functional unit of phytoremediation has been chosen as "phytoremediation of 1 ha of contaminated land for 1 year", and the functional unit of biorefinery and of the combined process as "processing 3 900 Mg of dry biomass" (this particular number is related to the planned capacity of the biorefinery). The two subprocesses and their functional units are connected with each other via the reference flow "1 kg of biomass harvested from the site and processed at the biorefinery". Biofuels and bio-coke are considered as by-products and the multifunctionality is handled by means of system expansion and credit. The final use of produced fuels is only considered in terms of their combustion, in order to differentiate between biogenic and non-biogenic greenhouse gas emissions. Consequently, the copper smelting process is excluded from the system boundary. Due to potentially broad impact of Phy2Climate project on all three "areas of protection", a decision has been made to include all standard impact categories of LCA: climate change / greenhouse effect, stratospheric ozone depletion, human toxicity, particulate matter formation, ionizing radiation, photochemical ozone formation, acidification, eutrophication, ecotoxicity, land use, consumption (depletion) of abiotic resources, use (depletion) of fresh water.

The second step is collecting Life Cycle Inventory (LCI) data. The LCI data for phytoremediation (e.g., amounts of energy and fuels, fertilizers, soil amendments, pesticides and water) has been collected by pilot site leaders. A very important element of the life cycle inventory of phytoremediation is the information on the amount of removed (or degraded) soil contaminants. However, this quantity cannot be directly measured and instead has to be estimated basing on the measurements of contaminant concentrations in the soil and/or biomass, which introduces a high dose of uncertainty. Inventory data on the mass balance of the biorefinery have been taken from previous experiments and theoretical calculations. For the energy balance of the biorefinery, a literature review supported by own mathematical models has been used to procure secondary data. Since the final technological design of the biorefinery has not been decided yet, a basic scenario without internal heat and mass streams recirculation was considered in this deliverable, as the first approach to the biorefinery concept. For easier readability and interpretation of the results, the inventory elements have been aggregated into five groups for phytoremediation and into 10 groups for biomass processing.

The last steps are performing Life Cycle Impact Assessment (LCIA) and its interpretation. Positive numerical values of environmental impact indicators should be interpreted as a burden on the environment, and negative values as avoided burden. The obtained results of the LCIA for phytoremediation show that consumption of fuel is the greatest contributor to almost all impact categories. Only the use of fertilizers has a comparable impact in some categories. Removal of contaminants from the soil has a beneficial impact on categories *Ecotoxicity* and *Human toxicity*. These beneficial impacts generally outweigh the adverse impacts caused by other groups of activities, resulting in an overall negative values of these environmental impact indicators. As the measurements of soil composition report an increase of carbon content in the soil in three out of four pilot sites, LCIA in the *Climate Change, land use and land use change* category shows a high positive environmental impact. These results are however very uncertain.

For the biomass processing subprocess, three groups of activities negatively stand out in the LCIA: Drying and pelletizing, Gas to Liquid (GtL) and Electrooxidation. This is a result of high consumption of heat and electric energy in these activities, and in the case of GtL also the use of external hydrogen. Even though the avoided use of fossil fuels, especially coke, results in reductions of greenhouse gas emissions, they are outweighed by the emissions associated with energy consumption in the biorefinery and, as a result, the overall impact of the biorefinery in the field of *Climate change* is adverse. In fact, the only categories in which the biorefinery gets a positive environmental score, are *Ecotoxicity, freshwater* and *Human toxicity, cancer inorganics*.

LCIA of averaged phytoremediation combined with biomass processing shows positive impact of the proposed technology on the *Ecotoxicity* and *Human toxicity* impact categories, as well as *Land use*. However, the environmental impacts in all other categories (except for the uncertain *Climate Change, land use and land use change* category) are adverse. This is a direct consequence of negative energy balance of the system and assumed utilization of non-renewable energy sources for driving the biorefinery (quantified in the *Resource use, fossils* impact category). Hence, these results should be interpreted with caution as they present the pessimistic case with high input of external energy required. In practice, the specific fuel consumption for agricultural activities can be lowered by scaling up the phytoremediation sites, and the specific energy consumption of biorefinery can be lowered by optimizing its configuration.

The presented preliminary results indicate the weakest points of the investigated technology and highlight the potential for improvements in the energy concept of the biorefinery. Works on optimization of the biorefinery concept should be carried out in the next phases of the project in tight cooperation with business model plans. Selected scenarios identified as the most promising can be evaluated using LCA approach proposed hereby, and a sensitivity analysis should allow estimating conditions that will ensure positive environmental impact of the phytoremediation-biorefinery system.

2 INTRODUCTION

One of the aims of the Phy2Climate project is to perform an environmental assessment of the investigated phytoremediation and biofuel production technology. This report presents the results of the first iteration of Life Cycle Assessment of Phy2Climate.

Life Cycle Assessment (LCA) is a methodology commonly used to evaluate the impacts of various processes or products on the natural environment, considering all stages of the life cycle: from obtaining the materials needed for production, through the manufacturing process, usage to liquidation and waste management. It is also called a „cradle to grave” analysis. The procedure of LCA is standardized [1] and contains the following phases [2]:

- Definition of goal and scope of the analysis. The analysed process or product must be precisely defined. Application of the study and the level of detail must be determined. Technological, geographical and temporal boundaries of the analysed system must be delineated. A „functional unit”, to which the numerical results of the analysis will be referred must be defined. A set of impact assessment indicators appropriate to the study must be chosen.
- Life cycle inventory (LCI). All relevant flows of substances and energy crossing the boundary of the analyzed system, must be identified and quantified. This stage requires compiling a diagram of flows between various sub-processes which constitute the analyzed process.
- Life cycle impact assessment (LCIA). The results of the Inventory stage must be assigned to relevant impact categories and subsequently characterized (recalculated into impact indicators). The results can also be normalized to facilitate a comparative analysis.
- Interpretation. Results from the Assessment phases shall be critically analysed and interpreted. Limitations of the performed study should be discussed and conclusions should be drawn. A legible report from the study, tailored to the target audience, should be prepared.

The subsequent chapters of this report correspond to the abovementioned phases of LCA.

Chapter 3 contains the first phase of LCA, that is Goal and Scope definition. Among others, the functional unit, system boundaries and analysed impact categories are defined.

Chapter 4 presents the Life Cycle Inventory. All relevant data on the use of materials and energy during phytoremediation and biomass processing (together with related components of the LCA model), collected from the project partners or from literature review, are listed and explained. Assumptions and omissions in the model are described.

In chapters 5 and 6, results of Life Cycle Impact Assessment are presented in the form of tables and subsequently interpreted. The numerical values are calculated for “impact categories”. There are two levels of impact categories: midpoint (specific impact categories) and endpoint (areas of protection). Impact categories at the midpoint level are defined at the place where a common mechanism for a variety of substances within that specific impact category exists. Endpoint modelling then consists of additionally characterising the severity or consequences and aggregating them to the three Areas of Protection (damage categories): human health, natural environment and natural resources. In general, the results on midpoint level are more accurate and precise compared to those at endpoint level [2], [3]. Below is a list of midpoint impact categories commonly used in LCA, together with their exemplary category indicators (units) [3], [4], [5]:

- climate change / greenhouse effect (kg CO_2 equivalents),
- stratospheric ozone depletion (kg CFC11 equivalents),
- human toxicity (disability adjusted lost life years),
- particulate matter formation (kg particulate matter)
- ionizing radiation (kg uranium-235 equivalent),

- photochemical ozone formation (kg ethene equivalents),
- acidification (kg SO_2 equivalents),
- eutrophication (kg PO_4^{3-} equivalents),
- ecotoxicity (kg 1,4-dichlorobenzene equivalents)
- land use ($m^2 \cdot$ year)
- consumption (depletion) of abiotic resources (kg/year),
- use (depletion) of fresh water (kg/year).

There exist several harmonized LCIA methodologies. A LCIA methodology is understood as a selected set of impact categories together with characterization models for calculating the midpoint impacts, as well as assigning them to the endpoint damage categories. The most commonly used ones are CML, Eco-indicator 99, ReCiPe and Environmental Footprint [5]. This LCA uses the Environmental Footprint method, which is recommended by the European Commission [6].

3 GOAL & SCOPE DEFINITION

This section constitutes the definition of the goal (3.1) and the scope (3.2) of Life Cycle Assessment of the Phy2climate project.

3.1 Goal definition

The definition of the goal is the first step steering subsequent phases of LCA. It helps setting the scope and thus helps declaring frames for the Life Cycle Impact Assessment phase.

While defining the goal for LCA, six aspects must be considered [2]. In the following subsections, these issues are sequentially addressed and commented.

3.1.1 Intended application of the study

LCA together with the related social acceptance assessment of the Phy2Climate project are planned for Research & Development purposes. The goal of LCA is to evaluate the sustainability of phytoremediation of contaminated lands with subsequent production of biofuels and bio-coke from the harvested biomass. Since the investigated technology is characterized by low readiness level (TRL 3), it is important to identify the environmental impacts before taking it to a higher level (TRL 5) and commissioning a large-scale commercial plant. Results of the LCA can possibly help in optimization of some aspects of the technology, e.g. selection of plant species for phytoremediation. In the long term, the LCA could be treated as a decision support tool for policymakers and companies commercializing the technology.

3.1.2 Reasons for carrying out the study

The LCA of Phy2Climate project is mainly driven by the scientific need for understanding the ecological performance of the proposed technology. The technology is expected to have overall positive environmental impacts, especially in the area of greenhouse gas emissions, and performing LCA is necessary to confirm this supposition. Proving the environmental-friendly and sustainable nature of the proposed technology is pivotal in helping to overcome possible social and legal barriers and facilitating the commercialization of technology.

The decision context of this study falls within “Situation C1” as described in the ILCD handbook [2]. The study has a descriptive and accounting character, with inclusion of interactions with other systems and evaluation of benefits occurring outside of the analysed system.

3.1.3 Methodological limitations

Although the main focus of the study are the greenhouse gas emissions, it is not limited to this single impact; a set of other indicators typically used in LCAs will also be quantified.

Due to the structure of the ongoing project, LCA study of phytoremediation and biomass conversion is being carried out in parallel to the actual phytoremediation on the pilot sites and biomass conversion in the pilot biorefinery. For that reason, primary data may be unavailable until the final stages of the project. In place of the missing data, secondary (literature) data or assumptions will be used instead.

The results of assessment of phytoremediation may be strongly site-specific, mainly because of the differences in the type of contamination in the soil, but also for reasons such as different climate zones in the investigated geographical locations.

3.1.4 Target audience

Primarily, the results of the study will be presented internally before the partners of the project and the European Commission. The study will be disclosed to the public, and the following groups of external audiences may be potentially interested in the results:

- Owners of contaminated sites – because phytoremediation is an alternative to conventional site cleanup methods,
- Biomass suppliers and farmers – because phytoremediation will affect the potential of production of food, as well as supply and demand for biomass,
- Chemical, metallurgical and fuel industry – because of the potential of substituting conventional processes and fuels by the ones developed within the investigated project,
- Scientific community – because the project may enrich the understanding of site cleanup methods and biomass-based energy systems,
- Governing bodies and regulators – because the findings of the study may provide hints for shaping sustainable policy in the field of bioenergy and land use,
- Technical associations – because of the opportunity to expand the databases and statistics,
- General public and non-governmental organizations concerned about the pollution of soils and sustainable use of resources – because of the opportunity to raise awareness about these subjects.

3.1.5 Comparative aspect

In general, this study is not meant to have a comparative character; various site clean-up methods will not be compared. However, as carbon footprint of biomass-based energy systems is by default compared with carbon footprint of the replaced fossil-based energy systems, an indirect comparison between the traditional fuels and products of the investigated pathway will emerge. Another potentially comparative element of the study comes from the use of various plant species for phytoremediation and further conversion to biofuels; comparing the LCA results may help to choose the optimal one. It should be stressed that results from several pilot sites will be reported, which may be misinterpreted as comparison between these sites. This is not intended; such comparison would be unjustified due to the differences in level and type of pollution, as well as differences in climate zones.

3.1.6 Commissioner of the study

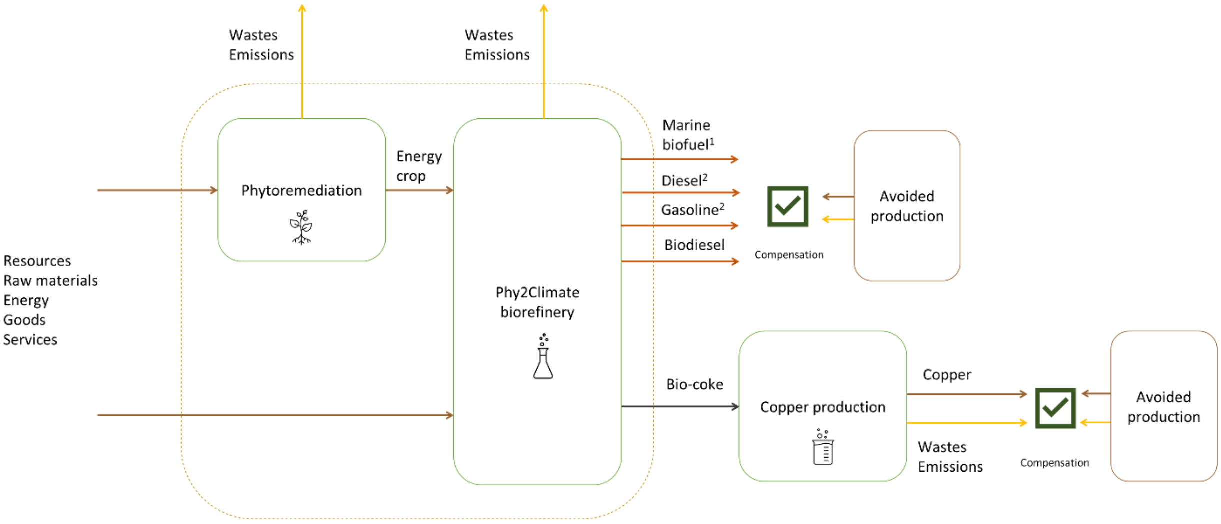
This study is within the scope of Phy2Climate project funded by European Commission from the European Union's Horizon 2020 research and innovation programme. The leader of the project is ITS Förderberatung GmbH, Austria. LCA is conducted by Department of Thermal Technology in Silesian University of Technology, Poland.

3.2 Scope definition

Section 3.2.1 contains the description of the system assessed in the LCA. In the following subsections, important aspects of the scope definition are described.

3.2.1 Description of the investigated system

The investigated technology consists of two main processes (subsystems). First, carefully selected crops will be planted on sites contaminated with hydrocarbons and/or heavy metals. In a process called phytoremediation, the plants extract or degrade the soil pollutants, so that the land can be restored for agricultural use. Second, harvested biomass is transported to a biorefinery, where (via a thermo-catalytic reforming process) it is converted into a variety of useful products: biofuels, which can substitute traditional fossil fuels in road and marine transport, and bio-coke, which can substitute petroleum coke in the metallurgical industry. In the case of soils contaminated with metals, these metals can additionally be recovered in the metal smelting process. The scheme of the Phy2Climate technology is presented in Figure 1.



1) TCR-oil based (ISO 8217)
2) TCR-gas based (Diesel EN 590, Gasoline EN 228)

Figure 1. Outline of the analysed process

The phytoremediation process requires the following activities. First, the soils will be characterized by physical and chemical analysis of collected samples. Sampling and analysis will be continued and periodically carried out during the phytoremediation process to monitor the progress in decontamination of the site. Second, pot trials in controlled conditions will be carried out in order to choose the optimal plant species and blend of soil amendments, fertilisers and biostimulants. The trials will also provide seeds for later transplantation to the pilot sites. In parallel, site preparation activities will be carried out. This includes terrain delimitation, area division into control and experimental parcels, soil ploughing and levelling and (if required) installation of irrigation equipment. After seeding and planting, the main cultivation phase will begin, which (depending on the site) involves fertilizing and/or irrigating. During this phase, plant growth will be carefully monitored and a sampling programme will be performed in order to determine, among others, the bioaccumulation factor for the contaminants. After harvesting, the energy crops will be analysed in order to determine their final contaminant content. For oleaginous plants, the oilseeds will be harvested and analysed separately from the straw. In case of lignocellulosic energy crops, the harvested biomass will be dried, chipped and pelletized. Depending on the energy crops and the site conditions, the crop cycle can be repeated up to three times. After the phytoremediation cycles are complete and the field research activities are fulfilled, the contaminated site will be decommissioned.

The harvested energy crops from the phytoremediation sites will be shipped to the biorefinery in form of bulk biomass. The biomass will be fed to the Thermo-Catalytic Reforming (TCR), which is a combination of intermediate pyrolysis with a post-reforming step. The TCR process produces bio-coke and three intermediate products: TCR-oil, TCR-gas and TCR-water. The TCR-oil distillation fractions are aimed to reach the ISO 8217 for distillate marine fuel (light fraction) and residual marine fuel (heavy fraction). The TCR-gas will feed Gas to Liquid (GtL) plant. The GtL will target the production of EN590 and EN228 gasoline as end products. The diesel and gasoline fractions will be produced via Fischer-Tropsch synthesis. Due to the natural composition of biomass in terms of stoichiometry, the C:H ratio is never enough to synthesise oxygen-free hydrocarbons from the gas product. For this reason, additional hydrogen is needed to ensure a high liquid yield and carbon use efficiency in the GtL process. To cover this need, TCR-water will be used as hydrogen source. The technology of Electro-oxidation will serve the two simultaneous purposes: purification of the TCR-water by oxidation of the residual organic compounds and hydrogen provision for the GtL by water electrolysis. This technology coupling builds a synergy loop of the process. The scheme of the technological pathway within the biorefinery is presented in Figure 2.

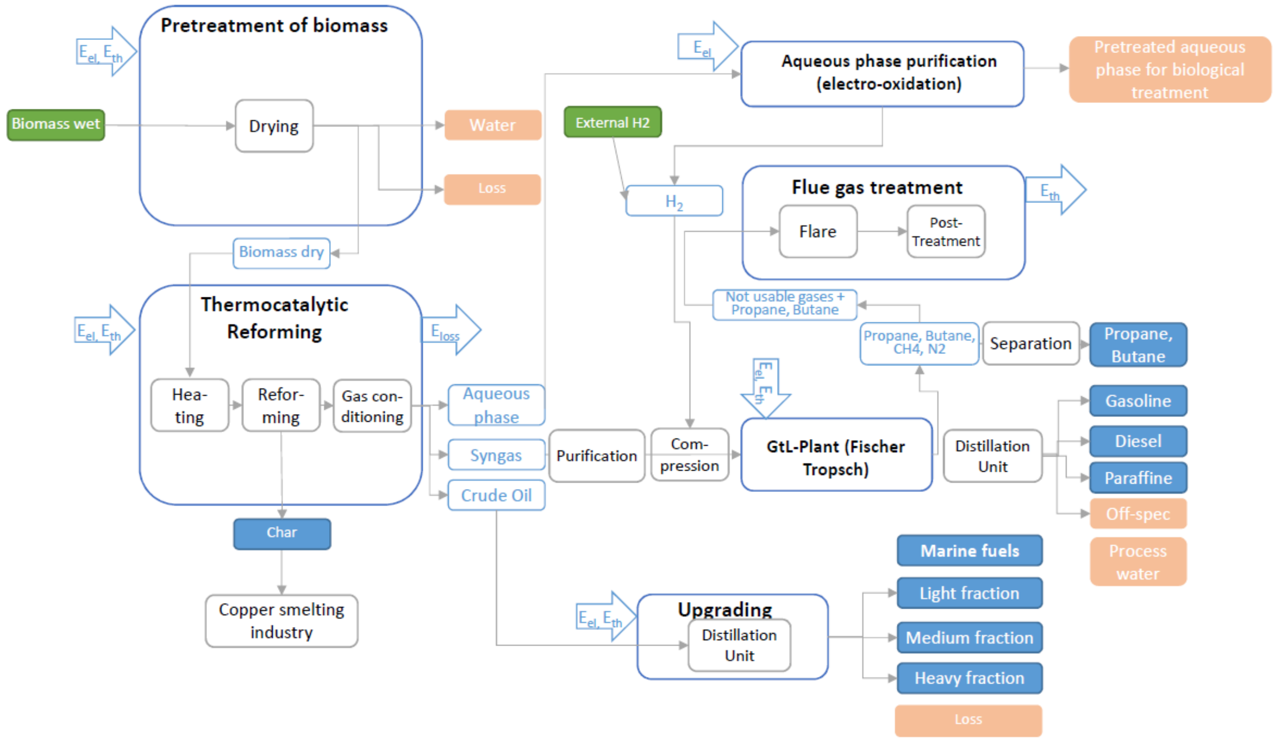


Figure 2. Technological scheme of the biorefinery

The project will be carried on four different sites (Argentina, Lithuania, Serbia, Spain) with four different contamination characteristics. Therefore, the LCA will actually consist of analyses of four different cases. All these cases will have the same framework.

3.2.2 Type of deliverable

Since the main application of the study is monitoring of environmental impacts of the investigated technology, the type of deliverable is a “Non-comparative Life Cycle Assessment study”.

3.2.3 Function of the system, functional unit and reference flows

As explained before, the investigated technology consists of two subsystems which can operate independently: phytoremediation, whose main function is the restoration of land to arable quality, and biorefinery, whose function is converting biomass into biofuels. These subsystems will be first assessed separately (using different functional units), and afterwards an assessment of the combined process will be carried out.

The main function of the phytoremediation technology is “**restoration of contaminated land to arable quality in under 20 years**”. With regard to this function, the functional unit is therefore chosen to be “**phytoremediation of 1 ha of contaminated land for 1 year**”.

Such definition of the functional unit does not fully reflect the function of the technology (in terms of soil quality), but adopting a seemingly more suitable definition - "phytoremediation of 1 ha of contaminated land to achieve arable quality" would cause problems with data acquisition. Furthermore, it could cause problems with interpretation of the results and combining this process with the biorefinery. The amount of time needed to achieve the desired effect will be different for different sites and different crops. Since the overall environmental impacts of Phy2Climate technology will depend on the utilization of harvested biomass due to environmental credits from production of biofuel, this may lead to phytoremediation processes which take longer time achieving more favourable (lower) environmental impacts, because more biofuels will be produced from the remediated land. This is not in line with the main function of the project, which is to restore the land as soon as possible.

The functional unit of biorefinery has been adopted as "**processing 3 900 Mg of dry biomass**". This particular number is related to the planned capacity of the biorefinery and corresponds to one year operation of the plant. Such definition of functional unit matches the assumptions in the business model of Phy2Climate, which is being developed in parallel.

The functional unit for the generalized combined process is equivalent to the functional unit of the biorefinery, but can be expressed as "**processing 3 900 Mg of dry biomass harvested from contaminated sites undergoing phytoremediation for one year**". The two subprocesses are connected with each other via the reference flow "**1 kg of biomass harvested from the site and processed at the biorefinery**". This reference flow is related to the area of remediated land through the biomass yield (expressed in kg per ha per year):

$$m_b = Y_b \cdot A_s \cdot \tau \tag{1}$$

where:

m_b – amount of harvested biomass, kg,
Y_b – yield of biomass, kg / (ha · year),
A_s – area of remediated site, ha,
τ – duration of the phytoremediation activity, year.

The reference flows of the biorefinery products – biofuels and bio-coke – will be expressed per unit of higher calorific value, as "**1 MJ of biofuel or bio-coke**".

3.2.4 LCI modelling framework

In line with the ILCD provisions for "Situation C1" [2], attributional modelling will be used. It is based on an assumption that the additional supply of products to the market is small enough not to affect the market in a noticeable way, hence it is considered as "static technosphere". Multifunctionality of the investigated technology, namely the production of biofuels and bio-coke, will be handled via the method of substitution (system expansion and credit). The substituted products are market-average fossil-derived fuels: coke, diesel, marine fuel and gasoline. The inventory of the substituted reference process will be subtracted from the inventory of the investigated technology.

3.2.5 System boundaries

The main processes included within the technological system boundary are depicted in Figure 3. The process "biofuel production" has previously been detailed in Figure 2. Background processes of the technosphere are not depicted; instead the blue arrows represent connections with these background processes such as supply of fuels and electric energy or production of fertilizers. Manufacturing of machines needed during the phytoremediation activities is excluded from the system boundary. Decommissioning of biorefinery is also not considered in the analysis – it is assumed that after the phytoremediation action is completed, the biorefinery will still process biomass from different sources. The final use of produced fuels is only considered in terms of their combustion, in order to differentiate between biogenic and non-biogenic greenhouse gas emissions. Consequently, the copper smelting process is excluded from the system boundary. This is justified by the fact that virtually the only difference between this process within the Phy2Climate project and the substituted process is the type of used coke and therefore excluding the copper smelting process would not change the outcome of the assessment. The metal and metalloid contaminants extracted from the soil are expected to translocate to bio-coke and eventually become admixtures of the produced copper. Under such scenario, these contaminants will not be re-released to the ecosphere.

Note that the process of plants cultivation may be interpreted as associated with negative emissions to the soil.

Construction phase of the biorefinery is not included in the inventory, in order to adhere to the provisions of greenhouse gas emissions included in the Renewable Energy Directive [7], which states that “emissions from the manufacture of machinery and equipment shall not be taken into account”. It is a common approach in LCA of energy conversion systems - especially those that involve combustion of fuels - to neglect the construction phase, because its impacts are low compared to the impacts of operation phase.

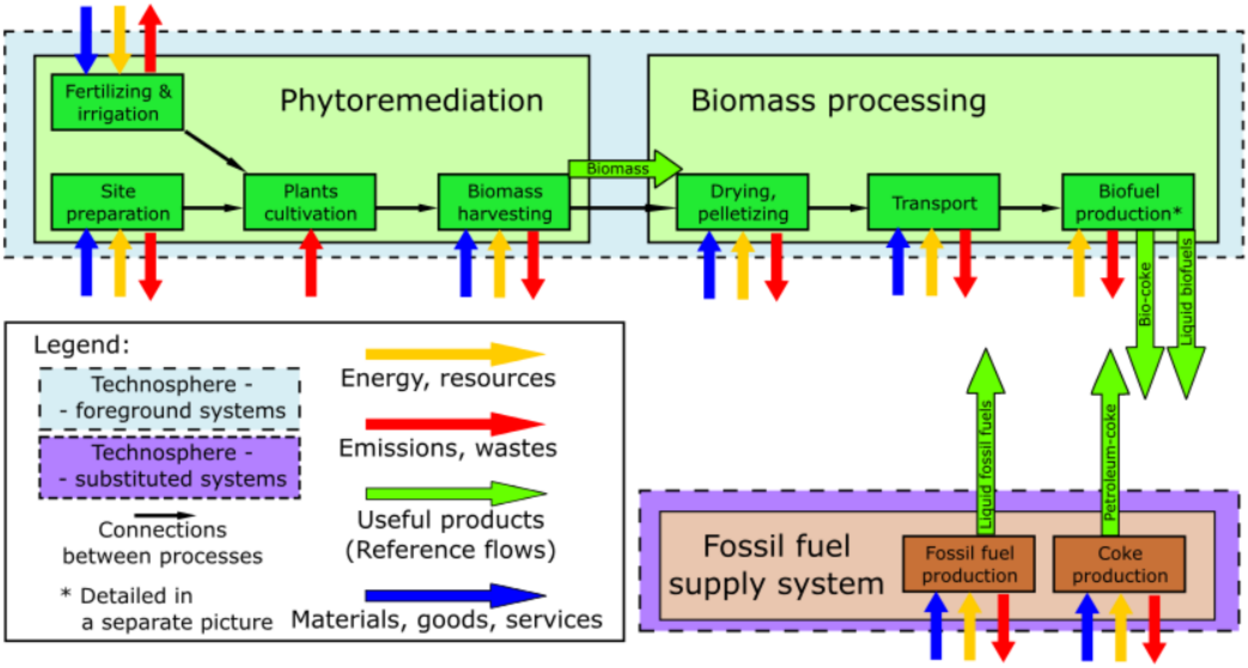


Figure 3. Technological system boundary

Even though phytoremediation activities are being carried out in four specific sites in Europe and South America, the geographical boundaries of LCA will not correspond to any particular region. For most of the inputs, generalized European datasets will be used. This is justified by the goal of the analysis, that is general assessment of sustainability of phytoremediation of contaminated lands with subsequent production of biofuels and by the fact that the project is primarily based in Europe.

The temporal system boundary is tied to the expected duration of phytoremediation activities, but it will not exceed 25 years.

The investigated system is not strongly dependent on external material flows. Generic datasets will be used for all the background processes (e.g. fertilizer production), which limits the need to establish cut-off criteria.

3.2.6 LCIA impact categories

The investigated technology has a potentially broad impact on all three "areas of protection", therefore a decision has been made not to exclude any of the standard impact categories. They are listed in Table 1. The analysis will be carried out using *LCA for Experts* software (by Sphera) with the use of Environmental Footprint 3.1 methodology. Environmental impacts will be assessed on the midpoint level. Weighting of results is not planned.

Table 1. List of impact categories investigated within the Environmental Footprint methodology

Area of protection	Natural environment	Human health	Natural resources
Impact categories	• Climate change (fossil, biogenic and land use change) • Ozone depletion • Ecotoxicity of freshwater (organics and inorganics) • Acidification • Eutrophication, marine • Eutrophication, freshwater • Eutrophication, terrestrial	• Human toxicity, cancer (organics and inorganics) • Human toxicity, non-cancer (organics and inorganics) • Particulate matter • Ionising radiation • Photochemical ozone formation	• Land use • Water use • Resource use, fossils • Resource use, minerals and metals

3.2.7 Sources of data and data quality

Life cycle inventory data for phytoremediation (in particular: amounts of energy and fuels, fertilizers, soil amendments, pesticides and water, as well as concentrations of contaminants in soil and biomass) has been collected directly by pilot site leaders, so it can be considered to have high quality. However, due to the time constraints of the project, some primary data from the phytoremediation pilot sites will be unavailable until the last months of the project. Data on background processes such as fertilizer production will be of secondary origin (average-market data), but nevertheless is expected to have good technological representativeness.

For the biorefinery process, primary data on mass balances will be procured directly from the developer of the technology and partner of the project – Fraunhofer, thus it will be characterized as being of high quality. However, final inventory data of biomass processing will be obtained in subsequent phases of the project when the whole biorefinery will be ready and when biomass from all pilot sites will be delivered and processed. For the first iterations of LCA, data on the mass balance of TCR have been taken from previous experiments on TCR reactor; mass balances of further processing steps (particularly GtL) are based on theoretical calculations performed by Fraunhofer. Some data on consumption auxiliary products have been obtained from literature reports supplemented with mathematical calculations.

For the energy balance of the biorefinery, a literature review supported by own mathematical models has been used to procure secondary data. The energy consumption of the biorefinery installation (primary data) is not directly measured during the laboratory-scale experiments for two reasons. First, the energy consumption is not linearly scalable and the LCA scenarios should account for the commercial scale facilities, and second, the experimental installation at Fraunhofer has not been optimised from the point of energy efficiency. The LCA calculations will be iteratively improved if new data will be available. More details on the sources of data are included in section 4.2.

For modelling of the substituted processes of fossil-based liquid fuels and coke production, average-market secondary data from the *LCA for Experts* software database will be used.

Regarding the time-related representativeness of secondary data, data for the reference year 2022 may be unavailable. In this case, the most recent datasets will be used. This should not significantly decrease the quality of the results, because the technology of the background processes does not change drastically over time.

4 LIFE CYCLE INVENTORY

The Inventory data presented in this section are split in two parts corresponding to the two main components of Phy2Climate technology, as presented in Figure 3. Section 4.1 covers the phytoremediation (agricultural) activities, and section 4.2 covers all further processing of harvested biomass. For the combined process of phytoremediation and biomass processing, a case based on averaged inventory data from the four pilot sites will be used.

4.1 Phytoremediation

Table 2 contains a summary of the general information on the pilot sites: types of contaminants, cultivated plants and area.

Table 2. Main information on the pilot sites

Site	**Argentina (ARG)**	**Serbia (SRB)**	**Lithuania (LTU)**	**Spain (ESP)**
Contaminants	Metals and metalloids	Heavy metals	Hydrocarbons	Hydrocarbons
Cultivated species	Native shrubs (plectrocarpa tetracantha, bulnesia retama, larrea cuneifolia, prosopis flexuosa), quinoa	Rapeseed	Herbaceous plants (tall fescue, perennial ryegrass, alfalfa, festuca perennis, bird's-foot trefoil), amaranthus, Jerusalem artichoke	Sorghum, rapeseed
Cultivated area	0.1 ha	0.24 ha	0.25 ha	0.80 ha

Pilot site leaders have been asked to provide inventory of the resources used during phytoremediation activities, in particular: amounts of energy and fuels, fertilizers, soil amendments, pesticides and water. Table 3 presents the summary of inventory; the listed values refer to 1 year of phytoremediation activity. The corresponding database items used in the modelling are also listed in the Table. They are of two types: **(E)** – elementary flows with assigned characterization factors (associated with emissions of substances to the ecosphere), and **(P)** – predefined processes included in the Sphera database (associated with production of goods).

For easier readability and interpretation of the LCIA results, the inventory elements of phytoremediation have been aggregated into five groups. The groups with the assigned colours are presented in Figure 4. The colours are used to highlight the corresponding elements of inventory in subsequent Tables. The same colours will be also used for presentation of results in Chapter 5.

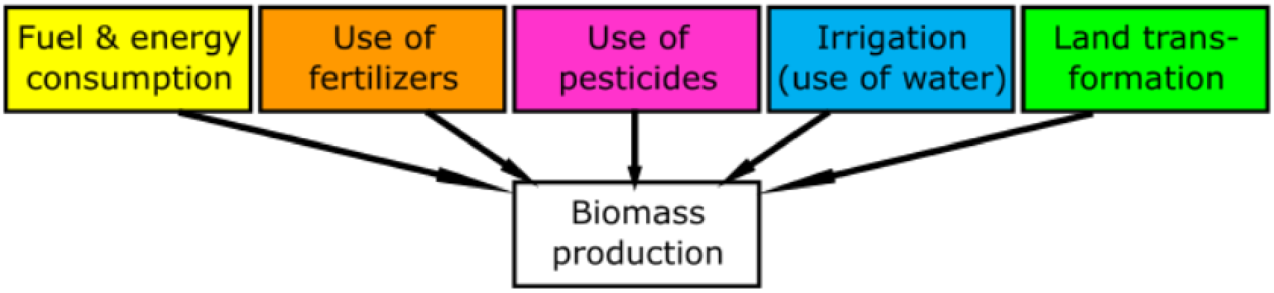


Figure 4. Groups of activities related to environmental impacts of phytoremediation

Table 3. Inventory of resources used during phytoremediation

Flow	Unit	Pilot site				Database item
		ARG	SRB	LTU	ESP	
Gasoline	dm^3	14.7	-	-	-	**(P)** RER: Gasoline mix (regular) at filling station
Diesel	dm^3	275	16,8	589.5	173	**(P)** RER: Diesel mix at filling station
Electric energy	kWh	-	-	150	-	**(P)** RER: Electricity grid mix
Freshwater	dm^3	190190	-	-	216240	**(E)** Fresh water [Water]
Rainwater	dm^3	-	45	9000	-	**(E)** Rain water [Water]
Compost[A]	kg	3360	-	1800	21.6	None[D]
Dolomite[B]	kg	95424	-	-	-	**(E)** Dolomite [Non renewable resources]
NPK fertilizer	kg	-	-	105	4	**(P)** DE: NPK 15-15-15
Urea	kg	6	-	-	-	**(P)** DE: Urea (agrarian)
Ammonium sulphate	kg	-	30	6	-	**(P)** DE: Ammonium sulphate (Caprolactam production)
Potassium chloride	kg	-	-	8	-	**(P)** RER: Potassium chloride (KCl/MOP, 60% K2O)
Cypermethrin	kg	-	0.008	-	-	**(P)** GLO: Pesticide (average) **(E)** Cypermethrin [Pesticides to agricultural soil]
Dicamba	kg	-	0.024	-	-	**(P)** GLO: Pesticide (average) **(E)** Dicamba [Pesticides to agricultural soil]
Dimoxystrobin	kg	-	0.008	-	-	**(P)** GLO: Pesticide (average) **(E)** Dimoxystrobin [Pesticides to agricultural soil]
Boscalid	kg	-	0.008	-	-	**(P)** GLO: Pesticide (average)
Biochar[C]	kg	-	-	-	10.8	None[E]

[A] For ARG and ESP, data was provided in m^3. Density of 400 kg/m^3 was assumed.
[B] Data was provided in m^3. Density of 2840 kg/m^3 was assumed.
[C] Data was provided in m^3. Density of 200 kg/m^3 was assumed.
[D] Production of compost has been excluded from the model.
[E] Biochar is also one of the products of the analyzed technology. A loop-back approach will be used.

The use of fuels has not been inventoried separately for each agricultural activity (e.g., soil preparation, fertilizing, harvest, transport). The presented numbers reflect aggregate fuel usage. Combustion of fuels has been modelled using the following processes: "*GLO: Universal Tractor Sphera*" for diesel and "*GLO: Car, petrol, Euro 4*" for gasoline.

Plant seeds and seedlings have been neglected in the analysis. This can be justified by the fact that seeds and seedlings are also products of the modelled process and as such can be "reused", remaining within the system boundary.

The fertilizers items listed in Table 3 indicated by **(P)** only cover the production of these fertilizers, not the emissions of substances to soil resulting from the application of these fertilizers. An attempt to account for these emissions is described further in this section.

Production of compost has not been included in the model. Compost, which is rather a by-product of utilization of biomass waste, is not produced specifically for the purpose of pilot sites, therefore including its production in the model (together with its potential positive environmental impacts) would be unjustified.

For pesticides, both their production and emissions to soil have been included in the model.

Land occupation by the phytoremediation site is not included in the inventory. This is because in the case of phytoremediation, the polluted land is not a "resource" that is used to fulfil the function of the system; it is rather a part of the system itself.

Even though phytoremediation for one year (assumed in the functional unit) is most likely not enough to achieve arable quality of the land, land transformation has been included in the life cycle inventory. Inventory elements used in the model are listed in Table 4. Area of land undergoing transformation has been listed in Table 2. Impacts associated with land transformation are assigned to the "Land transformation" group (per Figure 4).

Table 4. Land transformation inventory elements used in the LCA model

Pilot site	**Database items used for land transformation**	
ARG	From bare area (regionalized, AR)	To arable (regionalized, AR)
SRB	From field margins/hedgerows (regionalized, RS)	To arable (regionalized, RS)
LTU	From industrial area (regionalized, LT)	To arable (regionalized, LT)
ESP	From industrial area (regionalized, ES)	To arable (regionalized, ES)

Biomass production from the pilot sites after the first year is listed in Table 5.

Table 5. Dry biomass output from the pilot sites

Pilot site	**ARG**	**SRB**	**LTU**	**ESP**
Dry biomass output, kg	73[A]	2500[B]	370[C]	1118[D]
Biomass yield, kg/ha	727	10417	1480	1398

[A] Including: 56 kg of quinoa (harvested after the 1st year) and an estimate of 50 kg of native shrubs (to be harvested after the 3rd year)
[B] Estimate based on the number of plants and average dry mass of one plant at harvest
[C] Including: 160 kg of herbaceous plants, 167 kg of Jerusalem artichoke and 43 kg of amaranth
[D] Including: 1057 kg of sorghum and 61 kg of rape

A very important element of the life cycle inventory of phytoremediation is the information on the amount of removed (or degraded) soil contaminants. An absolute value (in kg) is required for the analysis. However, this quantity cannot be directly measured and instead has to be estimated. There are two possible approaches: one basing on the measurements of contaminant concentrations in the biomass – Equation (2), and another basing on the measurements of contaminant concentrations in the soil – Equation (3).

$$m_c = c_b \cdot m_b \tag{2}$$

$$m_c = \Delta c_s \cdot A_s \cdot d_s \cdot \rho_s \tag{3}$$

m_c – mass of removed contaminant, kg,
c_b – concentration of contaminant in biomass, kg / kg,
Δc_s – change of concentration of contaminant in soil, kg / kg,

d_s – depth of remediated soil, m,
ρ_s – density of remediated soil, kg / m^3.

This problem is not well documented in the literature and there is not a standard methodology of handling the decontamination of soil in LCA. It is not even common to include the (negative) emissions to soil in the inventory; often the aspect of decontamination is only addressed in the functional unit [8] (examples can be found in [9], [10]). Studies [11], [12] also do not include the negative emissions in the inventory, but estimate the amount of heavy metals removed from the soil using approach (2). Nevertheless, studies that include these emissions in the inventory can also be found [13].

Approach (2) is generally burdened with much lower uncertainty than approach (3). The main source of uncertainty is usually a very heterogenous spatial distribution of contaminants in the soil, which would require a very dense mesh of sampling points [14].

For the purpose of this study, the mass of heavy metals removed from the soil is estimated using approach (2), that is by multiplying the amount of harvested biomass by the average concentration of a given contaminant in the biomass. Unfortunately, this method cannot be applied in the case of hydrocarbons, which are degraded rather than extracted. For hydrocarbons, approach (3) is used, that is multiplying the change of their concentration in the soil by the mass of soil that undergoes phytoremediation. Such approach results in a rough estimate not only because of the abovementioned uncertainties of concentrations in soil, but also because the mass of soil is calculated by multiplying its volume by density. Since the actual density of soil has not been measured on the pilot sites, a value of 1500 kg/m^3 has been assumed. Depth of remediated soil has been assumed as 1 m. Calculations with formula (3) have been conducted separately for consecutive layers of soil (as measured and presented in Deliverable 2.3) and the results have been added together.

Results of calculations are presented in Table 6. The corresponding database items used in the modelling are also listed in the Table.

Formula (3) is also the only possibility to estimate the “emissions” of macronutrients (nitrogen, potassium, phosphorus, magnesium, calcium) as well as carbon into the soil. Results of calculations are presented in Table 7. Positive values represent an increase of content of a given element in the soil and negative values – a decrease. Since the presented results are very uncertain, and for some sites no measurements have been carried out, the changes of macronutrients content in the soil (except for carbon) are excluded from the life cycle inventory. This is also justified by the fact that the main focus of this LCA is the climate change impact category, which is not affected by these “emissions”. The changes of carbon content in the soil listed in Table 7 (after multiplying by a factor 44/12 to convert the mass of carbon to the mass of carbon dioxide) have been included in the model. The corresponding database item is **(E)** “*Carbon dioxide, to soil or biomass stock [Inorganic emissions to agricultural soil]*”.

There is one more potential component of the carbon balance: carbon content in the biomass residues that are left on the site after harvest. It has not yet been quantified and will be included in further iterations of the LCA.

Table 6. Inventory of contaminants removed from the soil (values in kg)

Contaminant	ARG	SRB	LTU	ESP	Database item
Arsenic	0.034180	-	-	-	**(E)** Arsenic [Heavy metals to agricultural soil]
Cadmium	0.050576	0.001900	-	-	**(E)** Cadmium [Heavy metals to agricultural soil]
Chromium	-	0.003675	-	-	**(E)** Chromium [Heavy metals to agricultural soil]
Copper	0.052904	0.013025	-	-	**(E)** Copper [Heavy metals to agricultural soil]
Lead	-	0.002100	-	-	**(E)** Lead [Heavy metals to agricultural soil]
Nickel	-	0.002700	-	-	**(E)** Nickel [Heavy metals to agricultural soil]
Zinc	0.334632	0.077625	-	-	**(E)** Zinc [Heavy metals to agricultural soil]
Total petroleum hydrocarbons	-	1019	2760	449	**(E)** Hydrocarbons, unspecified [Other emissions to agricultural soil]
Polycyclic aromatic hydrocarbons	-	4.11	-	3.81	**(E)** Polycyclic aromatic hydrocarbons (unspecified) [Organic emissions to agricultural soil]
Polychlorinated biphenyls	-	0.30	-	-	**(E)** Polychlorinated biphenyls (PCB unspecified) [Organic emissions to agricultural soil]

Table 7. Inventory of the changes of soil macronutrients and carbon (values in kg)

Element	ARG	SRB	LTU	ESP
Nitrogen		505	3394	-0.01
Potassium		-4309	-4869	-2366
Phosphorus		-1167	-1082	108
Magnesium		-34320	-29929	9243
Calcium	57654	-7863		38916
Carbon	16845	15840	33098	-2

4.2 Biomass processing

The subprocess “biomass processing” comprises the pretreatment of biomass (drying and pelletizing) which will be performed at the phytoremediated sites, transport of the pellets to the biorefinery and conversion of pellets into biofuels in the biorefinery. For the purpose of LCA the biorefinery could be treated as a “black box” process without distinguishing in detail between the various components of the biorefinery. However, the biorefinery has been split into particular processes to allow for a more detailed sensitivity analysis. Biorefinery products and the avoided use of replaced fossil fuels have been also split into three groups. The groups with the assigned colours are presented in Figure 5. The colours are used to highlight the corresponding elements of inventory in subsequent Tables. The same colours will be also used as legend in Chapter 5.

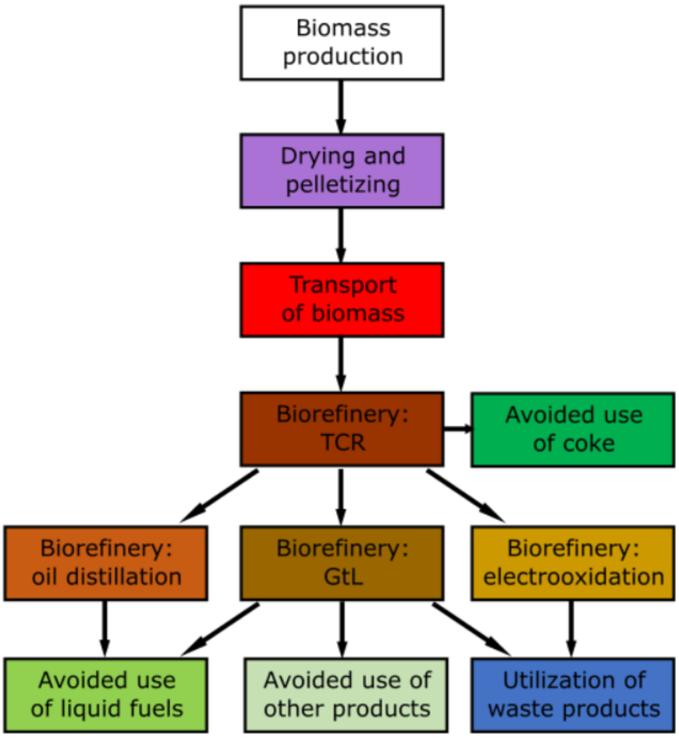


Figure 5. Groups of activities related to environmental impacts of biomass processing

As mentioned in section 3.2.7, the inventory of mass balance of biorefinery is mostly basing on previously conducted experiments on TCR reactor and theoretical calculations performed by Fraunhofer, and the energy balance and biomass pre-processing is mostly basing on secondary data obtained from literature reports and simulated with mathematical calculations. Tables in this section list the sources of data: **F** for Fraunhofer or **L** for own literature review. General process design, as presented in Figure 2, was used to identify energy and product streams for the LCI. A basic scenario without internal heat and mass streams recirculation was considered in this deliverable, as the first approach to the biorefinery concept. Case studies and biorefinery optimisation scheduled as Task 3.8 of Phy2Climate project will be used for different scenarios analysis at the later steps of LCA.

Biomass pretreatment involved drying, grinding, and pelletisation. Pelletized biomass is shipped to the biorefinery, where it undergoes thermochemical conversion into biochar, biooil, syngas, and pyrolysis water in the TCR reactor. Typically, the process is carried out under atmospheric pressure and inert atmosphere, with the reformer operating at around 700°C. Biochar produced in the TCR is destined for the copper smelter industry, not included in the biorefinery boundaries. Liquid and gaseous products are directed to the purification and conversion units. Pyrolysis water is a waste stream that, before exiting the biorefinery, is purified in the electrooxidation unit. Liquid products are produced in two ways. The first one is the distillation of biooil. The second liquid fuel production method is gas-to-liquid (GtL) conversion preceded by gas cooling, cleaning, and compression (all these processes are included in the "Biorefinery: GtL" group according to Figure 5). Hot syngas exits TCR reformer, thus, it was assumed that prior to the purification unit, it is cooled down. Gas purification unit is aimed at moisture, sulphur and nitrogen removal in the acidic and basic scrubbers, fixed bed reactors and a cooling trap. Purified syngas together with hydrogen generated in the electrooxidation unit is directed to a gas compressor. The base case scenario, following mass balance provided by Fraunhofer, assumes utilisation of CO as well as CO_2 in the GtL unit. The exact method, e.g., reversed water gas shift reaction, or direct Fischer–Tropsch conversion of CO_2, is not yet decided. A low-temperature Fischer–Tropsch reactor was assumed for the GtL unit. Liquid products (gasoline, kerosene and paraffin) are distilled in a separation column.

Assumptions used for the transport of biomass are the same as in the business model. A distance of 100 km and transport by trucks (a process **(P)** "*GLO: Truck-trailer, Euro 6 D-E, 34 - 40t gross weight / 27t payload capacity*") are assumed. The fuel consumed during transport is assumed to be **(P)** "*RER: Diesel mix at refinery*".

Table 8 presents the typical mass balance of the biorefinery for an input of 100 kg of dry biomass. The intermediate flows exchanged between the components of the biorefinery are irrelevant from the perspective of LCA, but they are useful for estimation of the energy balance of particular components of the refinery. The database items used for modelling are also listed in Table 8. For the produced biofuels, it is assumed that they will replace an equivalent amount of fossil fuels (in practice this is modelled by assuming negative flows of the replaced fossil fuels in the processes listed in Table 8). The use of biofuels is modelled by assuming positive emission of biogenic CO_2 from their combustion and equivalent negative emission of non-biogenic CO_2. Intermediate and final product distribution was provided by Fraunhofer, and this data comprised the preliminary test results as well as the predicted values for the processes still under development. The auxiliary material inputs identified were: surplus hydrogen for GtL plant (value provided by Fraunhofer); catalyst for GtL plant (estimated based on the literature review); and water and reagents for gas purification unit (estimated based on the literature review).

For the scrubbers, water consumption was calculated assuming 3:1 water to gas mass ratio [15]. Limestone required for sulfur removal was estimated based on data in [16]. Sulfuric acid amount that gives 5.6 pH of the acidic scrubber was assumed. Streams of removed contaminants - ammonia and calcium sulphate - were estimated based on the typical composition of agricultural residues, with the assumption that 95% of sulfur and 50% of nitrogen were transformed into H_2S and NH_3, respectively, during thermochemical conversion of biomass [17]. Hydrogen used in GtL partly comes from the electrooxidation step, but the remaining portion is assumed to come from non-renewable sources. Following Fraunhofer's recommendation, hydrogen demand for the GtL conversion accounted for all carbon species in syngas (2:1 ratio for CO and 3:1 ratio for CO_2) and the stoichiometric H_2 amount was further increased 2.5 times. Thus calculated hydrogen demand exceeded the amount produced within the biorefinery. Wastewater stream was estimated based on the reaction stoichiometry. Residual water from the biorefining process is assumed to be treated in standard municipal wastewater treatment system. Tail gas from the GtL, based on Fraunhofer data, comprised N_2 and residual combustible compounds such as methane, propane, and butane. Following the business model approach, it was assumed that propane/butane present in the tail gas is recovered and becomes a product for sale. Excess H_2 would also be present in the tail gas – in the base case scenario it is not separated and recirculated. Product distribution of GtL unit was provided by Fraunhofer, according to Schulz-Flory equation. Lastly, the catalyst demand for the FT synthesis was estimated based on [17], where the requirement for cobalt catalyst with a 5-year lifetime (when continuously replenished) was reported. The composition of the catalyst was assumed following [18], as 12 wt.% Co on SiO_2 support.

Table 8. Typical mass balance of biorefinery (amounts in kg)

Flow	Amount	Database item	Source
Dry biomass to TCR	100.0		
TCR-water	25.0		**F**
TCR-oil	4.0		**F**
TCR-gas	35.0		**F**
Biochar	36.0	**(P)** RER: Petroleum coke at refinery	**F**
Heavy fraction of marine fuel	0.82	**(P)** RER: Heavy fuel oil at refinery (1.0wt.% S)	**F**
Medium fraction of marine fuel	1.80	**(P)** RER: Diesel mix at refinery	**F**
Light fraction of marine fuel	1.18	**(P)** RER: Kerosene / Jet A1 at refinery	**F**
Hydrogen from electrooxidation	0.7		**F**
Wastewater from electrooxidation	24.29	**(P)** Municipal waste water treatment (variable sludge treatment)	**F**
Acid for gas purification	$1.03 \cdot 10^{-5}$	**(P)** RER: Sulphuric acid (96%)	**L**
Base for gas purification	29.4	**(P)** RER: RER: Limestone, crushed stone fines (Grain size 0/2) (EN15804 A1-A3)	**L**
Water for gas purification	210	**(P)** RER: Water (desalinated; deionised)	**L**
External hydrogen to GtL	4.69	**(P)** RER: Hydrogen (Europipeline)	**F**
Cobalt (catalyst) to GtL	$1.77 \cdot 10^{-4}$	**(P)** GLO: Cobalt, refined (metal) CI	**L**
Silica (catalyst support) to GtL	$1.3 \cdot 10^{-3}$	**(P)** DE: Silica sand (Excavation and processing)	**L**
Wastewater from GtL	225.48	**(P)** Municipal waste water treatment (variable sludge treatment)	**F + L**
Bio-diesel	1.92	**(P)** RER: Diesel mix at filling station	**F**
Bio-gasoline	3.59	**(P)** RER: Gasoline mix (regular) at filling station	**F**
Propane	1.06	**(P)** RER: Propane at refinery	**F**
Paraffins	0.49	**(P)** RER: Wax / Paraffins at refinery	**F**

The environmental impacts of the modelled biomass processing will result mainly from the consumption of energy at the various stages of biorefining. Below is a list of the database items used for the sources of energy:

- **(P)** "*RER: Thermal energy from natural gas*" for the consumption of heat,
- **(P)** "*RER: Electricity grid mix*" for the consumption of electric energy.

Table 9 lists the assumptions on energy used during biomass processing. Additionally, Table 10 lists the streams of waste heat generated in the biorefinery, which could be potentially reused (but in the basic scenario are not).

A belt dryer with a heat requirement of 1300 kWh/t of evaporated water and electric energy consumption of 32 kWh/t of dry biomass was foreseen for biomass drying [19]. Following the information from project partners, the decrease of moisture content from 84 to 10 wt.% was assumed, generating the evaporated water stream. In the base case scenario reusing this water was not considered. Electricity for grinding and pelletisation was estimated based on the specific energy demand for a conventional setup for woody biomass processing in a two-stage grinder and a mill pellet [20]. Electrical energy and heat demand for the TCR unit was provided by Fraunhofer, as it is in possession of an operating commercial scale reactor. Electrooxidation of pyrolysis water is a novel process currently under development in the scope of WP3, thus the energy requirement for this unit was also based on Fraunhofer measurements. For the remaining processes, energy demand and generation were estimated with thermodynamic calculations supported by literature reports, to avoid scale-up errors that could arise while using values measured during the laboratory-scale experiments. The heat duty of the distillation process was calculated assuming 47 MW heat required for 662.4 m^3/h oil distillation, and with the assumption of the light crude oil density of 850 kg/m^3 [21]. For the cooling of TCR-gas, it was assumed that it is cooled down from 700°C to 120°C. Recovered heat was calculated as the change in the physical enthalpy of the gas with the composition provided by Fraunhofer. Electrical energy requirement of the gas purification unit was assumed as 0.121 MJ/kg of syngas [17]. Compression of syngas combined with additional hydrogen was assumed as two-stage equal pressure rate compression (80% isentropic efficiency) with intercooling to 100°C [17]. To meet the requirements of the low-temperature Fischer–Tropsch synthesis, the outlet pressure and temperature were set to 25 bar and 250°C, respectively [17], [22], [23]. Power requirement and the heat generated during gas compression were calculated using Cantera thermodynamic properties library. Heat generated during the Fischer–Tropsch synthesis was estimated based on the standard enthalpy of reaction [24], and the heat recovered from the product separation column was calculated using specific heat capacity of gasoline, kerosene and paraffin [25], assuming cooling the products from 250°C to 20°C. The remaining tail gases from GtL (including methane and excess hydrogen) have a significant higher heating value of 179.4 MJ/kg. This energy could be recovered if the gases are combusted.

Table 9. Energy inputs to biomass processing (amounts in MJ per 100 kg of dry biomass)

Energy flow	Amount	Source
Heat for drying	1558.0	L
Electric energy for drying	11.4	L
Electric energy for grinding	49.39	L
Electric energy for pelletization	17.55	L
Heat for TCR	144.1	F
Electric energy for TCR	35.92	F
Heat for distillation	1.18	L
Electric energy for electrooxidation	396.3	F
Electric energy for gas purification	4.24	L
Electric energy for gas compression	158.37	L

Table 10. Waste heat streams in biorefinery (amounts in MJ per 100 kg of dry biomass)

Energy flow	Amount	Source
Heat generated during gas purification	32.86	L
Heat generated during gas compression	127.76	L
Heat generated in GtL	0.08	L
Heat generated in separation of GtL products	2.97	L
Heating value of tail gas from GtL	732.29	F

5 LIFE CYCLE IMPACT ASSESSMENT

The Environmental Footprint 3.1 methodology used in this LCA calculates 16 impact categories, which have been listed in Table 1. Some of these categories are additionally split into subcategories (e.g. fossil and biogenic climate change). All of them have been included in the assessment and presented in this deliverable. Section 5.1 presents the LCIA results for phytoremediation; section 5.2 presents the LCIA results for biomass processing, and section 5.3 presents the LCIA results for the combined process. All results in sections 5.1 and 5.2 are presented in the form of tables containing the absolute values of environmental impact indicators for groups of activities presented in Figure 4 and Figure 5, as well as their percentage contribution to the total. Since the environmental impacts can have both positive and negative values, the percentages have been calculated by dividing the value of environmental impact in the given group by the sum of absolute values of environmental impacts of all groups of activities. The percentage contributions therefore do not sum up to 100%, but their absolute values do. Positive values of the environmental impact indicators mean an adverse impact (burden) on the environment, while negative values mean that adverse impacts are avoided.

5.1 Phytoremediation

Environmental impacts of phytoremediation presented in this section have been calculated with regard to its functional unit "**phytoremediation of 1 ha of contaminated land for 1 year**". Tables 11 - 22 in section 5.1.1 present results of impact categories in the Natural Environment area of protection, particularly the Climate Change impact category. Tables 23 - 31 in section 5.1.2 present results of impact categories in the Human Health area of protection. Tables 32 - 35 in section 5.1.3 present results of impact categories in the Natural Resources area of protection.

5.1.1 Natural environment

Table 11. Life Cycle Impact Assessment of phytoremediation: Climate change - total

Climate Change - total	ARG		SRB		LTU		ESP	
	kg CO2 eq.	% of total	kg CO2 eq.	% of total	kg CO2 eq.	% of total	kg CO2 eq.	% of total
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	9.01E+01	0.01%	4.68E+01	0.02%	3.81E+02	0.08%	4.35E+00	0.66%
Use of pesticides	0.00E+00	0.00%	1.55E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	-6.18E+05	-98.33%	-2.42E+05	-99.89%	-4.85E+05	-98.36%	7.41E+00	1.13%
Fuel & energy consumption	1.04E+04	1.65%	2.09E+02	0.09%	7.73E+03	1.57%	6.44E+02	98.21%
Total	**-6.07E+05**		**-2.42E+05**		**-4.77E+05**		**6.56E+02**	

Table 12. Life Cycle Impact Assessment of phytoremediation: Climate change, biogenic

Climate Change, biogenic	ARG		SRB		LTU		ESP	
	kg CO2 eq.	% of total	kg CO2 eq.	% of total	kg CO2 eq.	% of total	kg CO2 eq.	% of total
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	4.74E-01	1.76%	1.27E-01	18.56%	1.31E+00	5.04%	1.52E-02	0.89%
Use of pesticides	0.00E+00	0.00%	7.95E-03	1.17%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Fuel & energy consumption	2.64E+01	98.24%	5.48E-01	80.27%	2.46E+01	94.96%	1.69E+00	99.11%
Total	**2.69E+01**	**100%**	**6.82E-01**	**100%**	**2.59E+01**	**100%**	**1.71E+00**	**100%**

Table 13. Life Cycle Impact Assessment of phytoremediation: Climate change, fossil

Climate Change, fossil	ARG		SRB		LTU		ESP	
	kg CO2 eq.	% of total	kg CO2 eq.	% of total	kg CO2 eq.	% of total	kg CO2 eq.	% of total
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	8.97E+01	0.87%	4.67E+01	18.36%	3.79E+02	4.73%	4.33E+00	0.68%
Use of pesticides	0.00E+00	0.00%	1.54E+00	0.61%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Fuel & energy consumption	1.03E+04	99.13%	2.06E+02	81.03%	7.64E+03	95.27%	6.37E+02	99.32%
Total	**1.04E+04**	**100%**	**2.54E+02**	**100%**	**8.02E+03**	**100%**	**6.41E+02**	**100%**

Table 14. Life Cycle Impact Assessment of phytoremediation: Climate change, land use and land use change

Climate Change, land use and land use change	ARG		SRB		LTU		ESP	
	kg CO2 eq.	% of total	kg CO2 eq.	% of total	kg CO2 eq.	% of total	kg CO2 eq.	% of total
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	1.15E-02	0.00%	2.87E-03	0.00%	1.29E-01	0.00%	1.52E-03	0.01%
Use of pesticides	0.00E+00	0.00%	3.15E-04	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	-6.18E+05	-99.99%	-2.42E+05	-100.00%	-4.85E+05	-99.99%	7.41E+00	55.94%
Fuel & energy consumption	8.92E+01	0.01%	1.89E+00	0.00%	6.37E+01	0.01%	5.83E+00	44.05%
Total	**-6.18E+05**		**-2.42E+05**		**-4.85E+05**		**1.32E+01**	

Table 15. Life Cycle Impact Assessment of phytoremediation: Ozone depletion

Ozone depletion	ARG		SRB		LTU		ESP	
	kg CFC-11 eq.	% of total	kg CFC-11 eq.	% of total	kg CFC-11 eq.	% of total	kg CFC-11 eq.	% of total
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	5.80E-10	30.08%	9.05E-11	71.78%	1.81E-09	11.66%	2.13E-11	20.61%
Use of pesticides	0.00E+00	0.00%	9.04E-12	7.18%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Fuel & energy consumption	1.35E-09	69.92%	2.65E-11	21.05%	1.38E-08	88.34%	8.20E-11	79.39%
Total	**1.93E-09**	**100%**	**1.26E-10**	**100%**	**1.56E-08**	**100%**	**1.03E-10**	**100%**

Table 16. Life Cycle Impact Assessment of phytoremediation: Ecotoxicity, freshwater - total

Ecotoxicity, freshwater - total	ARG		SRB		LTU		ESP	
	CTUe	% of total	CTUe	% of total	CTUe	% of total	CTUe	% of total
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	2.18E+02	0.08%	4.53E+02	2.93%	1.01E+03	1.30%	1.10E+01	0.10%
Use of pesticides	0.00E+00	0.00%	6.75E+02	4.37%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	-1.77E+05	-64.09%	-1.23E+04	-79.80%	-5.61E+03	-7.21%	-4.85E+03	-44.04%
Fuel & energy consumption	9.90E+04	35.83%	1.99E+03	12.89%	7.12E+04	91.49%	6.15E+03	55.86%
Total	**-7.78E+04**		**-9.21E+03**		**6.66E+04**		**1.31E+03**	

Table 17. Life Cycle Impact Assessment of phytoremediation: Ecotoxicity, freshwater inorganics

Ecotoxicity, freshwater inorganics	**ARG**		**SRB**		**LTU**		**ESP**	
	CTUe	**% of total**	**CTUe**	**% of total**	**CTUe**	**% of total**	**CTUe**	**% of total**
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	2.17E+02	0.08%	4.50E+02	7.91%	9.99E+02	1.40%	1.08E+01	0.18%
Use of pesticides	0.00E+00	0.00%	1.27E+01	0.22%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	-1.77E+05	-64.39%	-3.26E+03	-57.33%	0.00E+00	0.00%	0.00E+00	0.00%
Fuel & energy consumption	9.77E+04	35.53%	1.96E+03	34.54%	7.02E+04	98.60%	6.07E+03	99.82%
Total	**-7.91E+04**		**-8.34E+02**		**7.12E+04**		**6.08E+03**	

Table 18. Life Cycle Impact Assessment of phytoremediation: Ecotoxicity, freshwater organics

Ecotoxicity, freshwater organics	**ARG**		**SRB**		**LTU**		**ESP**	
	CTUe	**% of total**	**CTUe**	**% of total**	**CTUe**	**% of total**	**CTUe**	**% of total**
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	1.02E+00	0.08%	2.96E+00	0.03%	1.51E+01	0.23%	1.73E-01	0.00%
Use of pesticides	0.00E+00	0.00%	6.63E+02	6.79%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	0.00E+00	0.00%	-9.07E+03	-92.90%	-5.61E+03	-85.70%	-4.85E+03	-98.31%
Fuel & energy consumption	1.32E+03	99.92%	2.69E+01	0.28%	9.21E+02	14.07%	8.30E+01	1.68%
Total	**1.32E+03**		**-8.37E+03**		**-4.67E+03**		**-4.77E+03**	

Table 19. Life Cycle Impact Assessment of phytoremediation: Acidification

Acidification	**ARG**		**SRB**		**LTU**		**ESP**	
	mole of H+ eq.	**% of total**	**mole of H+ eq.**	**% of total**	**mole of H+ eq.**	**% of total**	**mole of H+ eq.**	**% of total**
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	1.71E-01	0.15%	5.63E-02	2.30%	4.47E-01	0.54%	5.14E-03	0.07%
Use of pesticides	0.00E+00	0.00%	3.38E-03	0.14%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Fuel & energy consumption	1.14E+02	99.85%	2.39E+00	97.57%	8.21E+01	99.46%	7.39E+00	99.93%
Total	**1.14E+02**	**100%**	**2.45E+00**	**100%**	**8.25E+01**	**100%**	**7.40E+00**	**100%**

Table 20. Life Cycle Impact Assessment of phytoremediation: Eutrophication, freshwater

Eutrophication, freshwater	**ARG**		**SRB**		**LTU**		**ESP**	
	kg P eq.	**% of total**	**kg P eq.**	**% of total**	**kg P eq.**	**% of total**	**kg P eq.**	**% of total**
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	1.80E-04	0.47%	4.41E-05	5.54%	4.85E-03	14.88%	5.76E-05	2.44%
Use of pesticides	0.00E+00	0.00%	5.76E-06	0.72%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Fuel & energy consumption	3.77E-02	99.53%	7.45E-04	93.74%	2.77E-02	85.12%	2.30E-03	97.56%
Total	**3.79E-02**	**100%**	**7.95E-04**	**100%**	**3.26E-02**	**100%**	**2.36E-03**	**100%**

Table 21. Life Cycle Impact Assessment of phytoremediation: Eutrophication, marine

Eutrophication, marine	**ARG**		**SRB**		**LTU**		**ESP**	
	kg N eq.	**% of total**	**kg N eq.**	**% of total**	**kg N eq.**	**% of total**	**kg N eq.**	**% of total**
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	6.02E-02	0.10%	2.00E-02	1.63%	2.64E-01	0.64%	3.08E-03	0.08%
Use of pesticides	0.00E+00	0.00%	7.78E-04	0.06%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Fuel & energy consumption	5.73E+01	99.90%	1.21E+00	98.31%	4.12E+01	99.36%	3.74E+00	99.92%
Total	**5.74E+01**	**100%**	**1.23E+00**	**100%**	**4.14E+01**	**100%**	**3.74E+00**	**100%**

Table 22. Life Cycle Impact Assessment of phytoremediation: Eutrophication, terrestrial

Eutrophication, terrestrial	**ARG**		**SRB**		**LTU**		**ESP**	
	mole of N eq.	**% of total**	**mole of N eq.**	**% of total**	**mole of N eq.**	**% of total**	**mole of N eq.**	**% of total**
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	7.51E-01	0.12%	1.53E-01	1.13%	1.93E+00	0.42%	2.24E-02	0.05%
Use of pesticides	0.00E+00	0.00%	8.07E-03	0.06%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Fuel & energy consumption	6.32E+02	99.88%	1.33E+01	98.81%	4.53E+02	99.58%	4.12E+01	99.95%
Total	**6.33E+02**	**100%**	**1.35E+01**	**100%**	**4.55E+02**	**100%**	**4.12E+01**	**100%**

5.1.2 Human health

Table 23. Life Cycle Impact Assessment of phytoremediation: Human toxicity, cancer - total

Human toxicity, cancer - total	**ARG**		**SRB**		**LTU**		**ESP**	
	CTUh	**% of total**	**CTUh**	**% of total**	**CTUh**	**% of total**	**CTUh**	**% of total**
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	1.41E-08	0.02%	1.13E-08	0.09%	4.42E-08	2.66%	4.94E-10	0.38%
Use of pesticides	0.00E+00	0.00%	3.69E-10	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	-6.50E-05	-96.90%	-1.21E-05	-99.56%	0.00E+00	0.00%	0.00E+00	0.00%
Fuel & energy consumption	2.06E-06	3.08%	4.16E-08	0.34%	1.62E-06	97.34%	1.29E-07	99.62%
Total	**-6.29E-05**		**-1.20E-05**		**1.66E-06**		**1.29E-07**	

Table 24. Life Cycle Impact Assessment of phytoremediation: Human toxicity, cancer inorganics

Human toxicity, cancer inorganics	**ARG**		**SRB**		**LTU**		**ESP**	
	CTUh	**% of total**	**CTUh**	**% of total**	**CTUh**	**% of total**	**CTUh**	**% of total**
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	6.67E-09	0.01%	8.78E-09	0.44%	2.10E-08	1.53%	2.29E-10	0.19%
Use of pesticides	0.00E+00	0.00%	2.18E-10	0.01%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	-6.50E-05	-97.09%	-1.95E-06	-97.59%	0.00E+00	0.00%	0.00E+00	0.00%
Fuel & energy consumption	1.94E-06	2.90%	3.92E-08	1.96%	1.35E-06	98.47%	1.21E-07	99.81%
Total	**-6.30E-05**		**-1.90E-06**		**1.38E-06**		**1.21E-07**	

Table 25. Life Cycle Impact Assessment of phytoremediation: Human toxicity, cancer organics

Human toxicity, cancer organics	**ARG**		**SRB**		**LTU**		**ESP**	
	CTUh	**% of total**	**CTUh**	**% of total**	**CTUh**	**% of total**	**CTUh**	**% of total**
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	7.46E-09	5.88%	2.49E-09	0.02%	2.32E-08	8.10%	2.66E-10	3.40%
Use of pesticides	0.00E+00	0.00%	1.51E-10	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	0.00E+00	0.00%	-1.01E-05	-99.95%	0.00E+00	0.00%	0.00E+00	0.00%
Fuel & energy consumption	1.19E-07	94.12%	2.44E-09	0.02%	2.63E-07	91.90%	7.55E-09	96.60%
Total	**1.27E-07**		**-1.01E-05**		**2.87E-07**		**7.81E-09**	

Table 26. Life Cycle Impact Assessment of phytoremediation: Human toxicity, non-cancer - total

Human toxicity, non-cancer - total	**ARG**		**SRB**		**LTU**		**ESP**	
	CTUh	**% of total**	**CTUh**	**% of total**	**CTUh**	**% of total**	**CTUh**	**% of total**
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	7.71E-07	0.01%	4.15E-07	0.13%	1.86E-06	2.11%	2.11E-08	0.13%
Use of pesticides	0.00E+00	0.00%	2.73E-06	0.86%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	-1.43E-02	-99.38%	-3.12E-04	-98.44%	-2.20E-05	-24.92%	-1.09E-05	-66.11%
Fuel & energy consumption	8.90E-05	0.62%	1.81E-06	0.57%	6.44E-05	72.97%	5.59E-06	33.76%
Total	**-1.42E-02**		**-3.07E-04**		**4.43E-05**		**-5.34E-06**	

Table 27. Life Cycle Impact Assessment of phytoremediation: Human toxicity, non-cancer inorganics

Human toxicity, non-cancer inorganics	**ARG**		**SRB**		**LTU**		**ESP**	
	CTUh	**% of total**	**CTUh**	**% of total**	**CTUh**	**% of total**	**CTUh**	**% of total**
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	7.42E-07	0.01%	4.10E-07	0.13%	1.81E-06	2.78%	2.05E-08	0.37%
Use of pesticides	0.00E+00	0.00%	1.52E-08	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	-1.43E-02	-99.39%	-3.02E-04	-99.28%	0.00E+00	0.00%	0.00E+00	0.00%
Fuel & energy consumption	8.75E-05	0.61%	1.78E-06	0.59%	6.33E-05	97.22%	5.50E-06	99.63%
Total	**-1.42E-02**		**-3.00E-04**		**6.51E-05**		**5.52E-06**	

Table 28. Life Cycle Impact Assessment of phytoremediation: Human toxicity, non-cancer organics

Human toxicity, non-cancer organics	**ARG**		**SRB**		**LTU**		**ESP**	
	CTUh	**% of total**	**CTUh**	**% of total**	**CTUh**	**% of total**	**CTUh**	**% of total**
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	2.90E-08	1.96%	5.17E-09	0.04%	5.28E-08	0.23%	6.13E-10	0.01%
Use of pesticides	0.00E+00	0.00%	2.72E-06	21.65%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	0.00E+00	0.00%	-9.80E-06	-78.08%	-2.20E-05	-95.22%	-1.09E-05	-99.17%
Fuel & energy consumption	1.45E-06	98.04%	2.94E-08	0.23%	1.05E-06	4.56%	9.07E-08	0.82%
Total	**1.48E-06**		**-7.05E-06**		**-2.09E-05**		**-1.09E-05**	

Table 29. Life Cycle Impact Assessment of phytoremediation: Particulate matter

Particulate matter	**ARG**		**SRB**		**LTU**		**ESP**	
	Disease incidences	**% of total**	**Disease incidences**	**% of total**	**Disease incidences**	**% of total**	**Disease incidences**	**% of total**
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	1.19E-06	0.05%	3.54E-07	0.73%	6.39E-06	0.39%	7.48E-08	0.05%
Use of pesticides	0.00E+00	0.00%	3.31E-08	0.07%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Fuel & energy consumption	2.26E-03	99.95%	4.78E-05	99.20%	1.62E-03	99.61%	1.48E-04	99.95%
Total	**2.26E-03**	**100%**	**4.82E-05**	**100%**	**1.63E-03**	**100%**	**1.48E-04**	**100%**

Table 30. Life Cycle Impact Assessment of phytoremediation: Ionising radiation, human health

Ionising radiation, human health	**ARG**		**SRB**		**LTU**		**ESP**	
	kBq U235 eq.	**% of total**	**kBq U235 eq.**	**% of total**	**kBq U235 eq.**	**% of total**	**kBq U235 eq.**	**% of total**
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	3.11E+00	7.27%	5.02E-01	37.72%	1.19E+01	2.79%	1.37E-01	5.38%
Use of pesticides	0.00E+00	0.00%	5.03E-02	3.78%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Fuel & energy consumption	3.96E+01	92.73%	7.78E-01	58.50%	4.14E+02	97.21%	2.40E+00	94.62%
Total	**4.27E+01**	**100%**	**1.33E+00**	**100%**	**4.26E+02**	**100%**	**2.54E+00**	**100%**

Table 31. Life Cycle Impact Assessment of phytoremediation: Photochemical ozone formation, human health

Photochemical ozone formation, human health	**ARG**		**SRB**		**LTU**		**ESP**	
	kg NMVOC eq.	**% of total**	**kg NMVOC eq.**	**% of total**	**kg NMVOC eq.**	**% of total**	**kg NMVOC eq.**	**% of total**
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	9.09E-02	0.06%	4.88E-02	1.42%	4.58E-01	0.40%	5.29E-03	0.05%
Use of pesticides	0.00E+00	0.00%	2.35E-03	0.07%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Fuel & energy consumption	1.61E+02	99.94%	3.39E+00	98.51%	1.15E+02	99.60%	1.05E+01	99.95%
Total	**1.61E+02**	**100%**	**3.45E+00**	**100%**	**1.16E+02**	**100%**	**1.05E+01**	**100%**

5.1.3 Natural resources

Table 32. Life Cycle Impact Assessment of phytoremediation: Land use

Land use	**ARG**		**SRB**		**LTU**		**ESP**	
	Pt	**% of total**	**Pt**	**% of total**	**Pt**	**% of total**	**Pt**	**% of total**
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	2.01E+02	0.01%	3.20E+01	0.00%	1.95E+03	0.00%	2.31E+01	0.00%
Use of pesticides	0.00E+00	0.00%	3.63E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	-1.80E+06	-96.94%	2.05E+06	99.94%	-7.23E+07	-99.94%	-5.77E+07	-99.99%
Fuel & energy consumption	5.66E+04	3.05%	1.16E+03	0.06%	4.49E+04	0.06%	3.59E+03	0.01%
Total	**-1.74E+06**		**2.05E+06**		**-7.23E+07**		**-5.77E+07**	

Table 33. Life Cycle Impact Assessment of phytoremediation: Resource use, fossils

Resource use, fossils	**ARG**		**SRB**		**LTU**		**ESP**	
	MJ	**% of total**	**MJ**	**% of total**	**MJ**	**% of total**	**MJ**	**% of total**
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	2.08E+03	1.48%	9.81E+02	25.87%	5.54E+03	4.87%	6.24E+01	0.72%
Use of pesticides	0.00E+00	0.00%	3.31E+01	0.87%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Fuel & energy consumption	1.38E+05	98.52%	2.78E+03	73.25%	1.08E+05	95.13%	8.58E+03	99.28%
Total	**1.40E+05**	**100%**	**3.79E+03**	**100%**	**1.14E+05**	**100%**	**8.64E+03**	**100%**

Table 34. Life Cycle Impact Assessment of phytoremediation: Resource use, minerals and metals

Resource use, minerals and metals	**ARG**		**SRB**		**LTU**		**ESP**	
	kg Sb eq.	**% of total**	**kg Sb eq.**	**% of total**	**kg Sb eq.**	**% of total**	**kg Sb eq.**	**% of total**
Irrigation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Use of fertilizers	5.19E-06	0.78%	3.41E-06	5.35%	1.32E-04	19.03%	1.56E-06	3.61%
Use of pesticides	0.00E+00	0.00%	4.68E-05	73.44%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Fuel & energy consumption	6.62E-04	99.22%	1.35E-05	21.21%	5.63E-04	80.97%	4.18E-05	96.39%
Total	**6.67E-04**	**100%**	**6.37E-05**	**100%**	**6.95E-04**	**100%**	**4.33E-05**	**100%**

Table 35. Life Cycle Impact Assessment of phytoremediation: Water use

Water use	**ARG**		**SRB**		**LTU**		**ESP**	
	m^3 world equiv.	**% of total**	**m^3 world equiv.**	**% of total**	**m^3 world equiv.**	**% of total**	**m^3 world equiv.**	**% of total**
Irrigation	8.17E+04	99.83%	0.00E+00	0.00%	0.00E+00	0.00%	1.16E+04	99.93%
Use of fertilizers	1.74E-01	0.00%	2.72E-01	9.71%	6.46E+00	2.64%	7.49E-02	0.00%
Use of pesticides	0.00E+00	0.00%	6.46E-02	2.31%	0.00E+00	0.00%	0.00E+00	0.00%
Land transformation	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%	0.00E+00	0.00%
Fuel & energy consumption	1.37E+02	0.17%	2.46E+00	87.98%	2.38E+02	97.36%	7.61E+00	0.07%
Total	**8.18E+04**	**100%**	**2.80E+00**	**100%**	**2.45E+02**	**100%**	**1.16E+04**	**100%**

5.2 Biomass processing

Environmental impacts of biomass processing presented in this section have been calculated with regard to its functional unit “**processing 3 900 Mg of dry biomass**”. Tables 36 - 47 in section 5.2.1 present results of impact categories in the Natural Environment area of protection, particularly the Climate Change impact category. Tables 48 - 56 in section 5.2.2 present results of impact categories in the Human Health area of protection. Tables 57 - 60 in section 5.2.3 present results of impact categories in the Natural Resources area of protection.

5.2.1 Natural environment

Table 36. Life Cycle Impact Assessment of biomass processing: Climate change – total

Climate Change - total	**kg CO2 eq.**	**% of total**
Drying and pelletizing	4.36E+06	29.47%
Transport of biomass	2.89E+04	0.19%
Biorefinery: TCR	5.04E+05	3.41%
Biorefinery: GTL	1.30E+06	8.76%
Biorefinery: oil distillation	3.10E+03	0.02%
Biorefinery: electrooxidation	1.40E+06	9.47%
Utilization of waste products	5.52E+03	0.04%
Avoided use of liquid fuels	-1.32E+06	-8.91%
Avoided use of coke	-5.71E+06	-38.59%
Avoided use of other products	-1.67E+05	-1.13%
Total	**4.04E+05**	

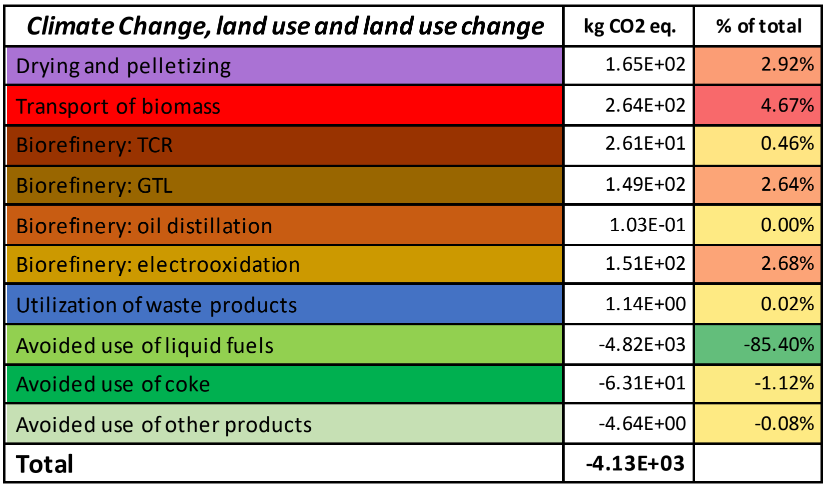
Table 37. Life Cycle Impact Assessment of biomass processing: Climate change, biogenic

Climate Change, biogenic	**kg CO2 eq.**	**% of total**
Drying and pelletizing	7.79E+03	21.78%
Transport of biomass	7.41E+01	0.21%
Biorefinery: TCR	1.60E+03	4.49%
Biorefinery: GTL	7.52E+03	21.03%
Biorefinery: oil distillation	4.08E+00	0.01%
Biorefinery: electrooxidation	1.23E+04	34.31%
Utilization of waste products	1.26E+03	3.53%
Avoided use of liquid fuels	-2.12E+03	-5.94%
Avoided use of coke	-2.90E+03	-8.11%
Avoided use of other products	-2.15E+02	-0.60%
Total	**2.53E+04**	

Table 38. Life Cycle Impact Assessment of biomass processing: Climate change, fossil

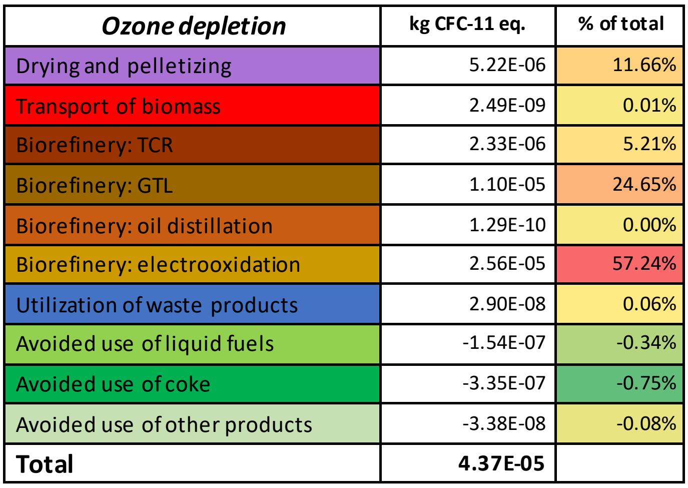
Climate Change, fossil	**kg CO2 eq.**	**% of total**
Drying and pelletizing	4.35E+06	29.50%
Transport of biomass	2.85E+04	0.19%
Biorefinery: TCR	5.03E+05	3.41%
Biorefinery: GTL	1.29E+06	8.73%
Biorefinery: oil distillation	3.10E+03	0.02%
Biorefinery: electrooxidation	1.39E+06	9.41%
Utilization of waste products	4.26E+03	0.03%
Avoided use of liquid fuels	-1.31E+06	-8.89%
Avoided use of coke	-5.71E+06	-38.68%
Avoided use of other products	-1.67E+05	-1.13%
Total	**3.83E+05**	

Table 39. Life Cycle Impact Assessment of biomass processing: Climate change, land use and land use change



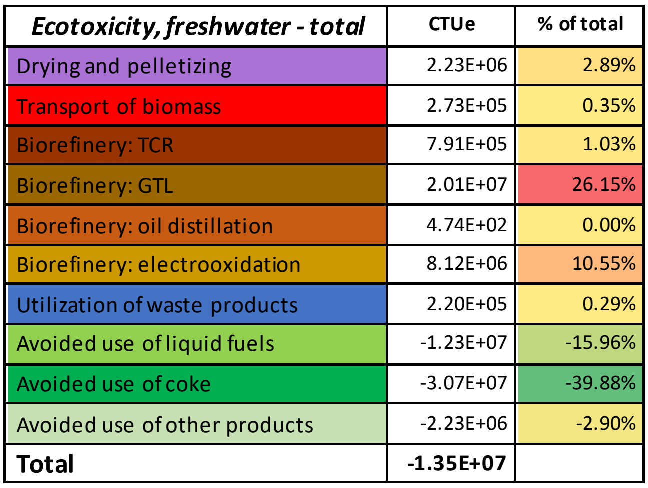
Climate Change, land use and land use change	**kg CO2 eq.**	**% of total**
Drying and pelletizing	1.65E+02	2.92%
Transport of biomass	2.64E+02	4.67%
Biorefinery: TCR	2.61E+01	0.46%
Biorefinery: GTL	1.49E+02	2.64%
Biorefinery: oil distillation	1.03E-01	0.00%
Biorefinery: electrooxidation	1.51E+02	2.68%
Utilization of waste products	1.14E+00	0.02%
Avoided use of liquid fuels	-4.82E+03	-85.40%
Avoided use of coke	-6.31E+01	-1.12%
Avoided use of other products	-4.64E+00	-0.08%
Total	**-4.13E+03**	

Table 40. Life Cycle Impact Assessment of biomass processing: Ozone depletion



Ozone depletion	**kg CFC-11 eq.**	**% of total**
Drying and pelletizing	5.22E-06	11.66%
Transport of biomass	2.49E-09	0.01%
Biorefinery: TCR	2.33E-06	5.21%
Biorefinery: GTL	1.10E-05	24.65%
Biorefinery: oil distillation	1.29E-10	0.00%
Biorefinery: electrooxidation	2.56E-05	57.24%
Utilization of waste products	2.90E-08	0.06%
Avoided use of liquid fuels	-1.54E-07	-0.34%
Avoided use of coke	-3.35E-07	-0.75%
Avoided use of other products	-3.38E-08	-0.08%
Total	**4.37E-05**	

Table 41. Life Cycle Impact Assessment of biomass processing: Ecotoxicity, freshwater – total



Ecotoxicity, freshwater - total	**CTUe**	**% of total**
Drying and pelletizing	2.23E+06	2.89%
Transport of biomass	2.73E+05	0.35%
Biorefinery: TCR	7.91E+05	1.03%
Biorefinery: GTL	2.01E+07	26.15%
Biorefinery: oil distillation	4.74E+02	0.00%
Biorefinery: electrooxidation	8.12E+06	10.55%
Utilization of waste products	2.20E+05	0.29%
Avoided use of liquid fuels	-1.23E+07	-15.96%
Avoided use of coke	-3.07E+07	-39.88%
Avoided use of other products	-2.23E+06	-2.90%
Total	**-1.35E+07**	

Table 42. Life Cycle Impact Assessment of biomass processing: Ecotoxicity, freshwater inorganics

Ecotoxicity, freshwater inorganics	CTUe	% of total
Drying and pelletizing	2.20E+06	2.89%
Transport of biomass	2.70E+05	0.35%
Biorefinery: TCR	7.87E+05	1.03%
Biorefinery: GTL	2.00E+07	26.15%
Biorefinery: oil distillation	4.63E+02	0.00%
Biorefinery: electrooxidation	8.09E+06	10.60%
Utilization of waste products	2.18E+05	0.29%
Avoided use of liquid fuels	-1.22E+07	-15.93%
Avoided use of coke	-3.04E+07	-39.86%
Avoided use of other products	-2.21E+06	-2.90%
Total	**-1.33E+07**	

Table 43. Life Cycle Impact Assessment of biomass processing: Ecotoxicity, freshwater organics

Ecotoxicity, freshwater organics	CTUe	% of total
Drying and pelletizing	2.07E+04	3.02%
Transport of biomass	3.05E+03	0.45%
Biorefinery: TCR	4.22E+03	0.62%
Biorefinery: GTL	1.81E+05	26.53%
Biorefinery: oil distillation	1.09E+01	0.00%
Biorefinery: electrooxidation	3.20E+04	4.69%
Utilization of waste products	2.71E+03	0.40%
Avoided use of liquid fuels	-1.33E+05	-19.39%
Avoided use of coke	-2.86E+05	-41.87%
Avoided use of other products	-2.08E+04	-3.04%
Total	**-1.95E+05**	

Table 44. Life Cycle Impact Assessment of biomass processing: Acidification

Acidification	mole of H+ eq.	% of total
Drying and pelletizing	3.03E+03	24.66%
Transport of biomass	2.47E+01	0.20%
Biorefinery: TCR	4.93E+02	4.02%
Biorefinery: GTL	2.72E+03	22.20%
Biorefinery: oil distillation	1.85E+00	0.02%
Biorefinery: electrooxidation	2.97E+03	24.19%
Utilization of waste products	1.08E+01	0.09%
Avoided use of liquid fuels	-8.76E+02	-7.15%
Avoided use of coke	-1.99E+03	-16.26%
Avoided use of other products	-1.48E+02	-1.21%
Total	**6.23E+03**	

Table 45. Life Cycle Impact Assessment of biomass processing: Eutrophication, freshwater

Eutrophication, freshwater	**kg P eq.**	**% of total**
Drying and pelletizing	1.29E+00	5.81%
Transport of biomass	1.04E-01	0.47%
Biorefinery: TCR	4.92E-01	2.22%
Biorefinery: GTL	3.36E+00	15.17%
Biorefinery: oil distillation	2.01E-04	0.00%
Biorefinery: electrooxidation	5.18E+00	23.40%
Utilization of waste products	6.02E+00	27.21%
Avoided use of liquid fuels	-4.31E+00	-19.45%
Avoided use of coke	-1.29E+00	-5.83%
Avoided use of other products	-9.85E-02	-0.44%
Total	**1.08E+01**	

Table 46. Life Cycle Impact Assessment of biomass processing: Eutrophication, marine

Eutrophication, marine	**kg N eq.**	**% of total**
Drying and pelletizing	1.20E+03	35.20%
Transport of biomass	6.58E+00	0.19%
Biorefinery: TCR	1.62E+02	4.76%
Biorefinery: GTL	7.17E+02	21.11%
Biorefinery: oil distillation	8.02E-01	0.02%
Biorefinery: electrooxidation	7.10E+02	20.90%
Utilization of waste products	2.56E+01	0.75%
Avoided use of liquid fuels	-1.99E+02	-5.87%
Avoided use of coke	-3.54E+02	-10.41%
Avoided use of other products	-2.62E+01	-0.77%
Total	**2.24E+03**	

Table 47. Life Cycle Impact Assessment of biomass processing: Eutrophication, terrestrial

Eutrophication, terrestrial	**mole of N eq.**	**% of total**
Drying and pelletizing	1.32E+04	36.10%
Transport of biomass	8.53E+01	0.23%
Biorefinery: TCR	1.75E+03	4.80%
Biorefinery: GTL	7.59E+03	20.82%
Biorefinery: oil distillation	8.89E+00	0.02%
Biorefinery: electrooxidation	7.42E+03	20.34%
Utilization of waste products	3.30E+01	0.09%
Avoided use of liquid fuels	-2.21E+03	-6.06%
Avoided use of coke	-3.92E+03	-10.74%
Avoided use of other products	-2.90E+02	-0.80%
Total	**2.36E+04**	

5.2.2 Human health

Table 48. Life Cycle Impact Assessment of biomass processing: Human toxicity, cancer – total

Human toxicity, cancer - total	CTUh	% of total
Drying and pelletizing	6.02E-04	23.67%
Transport of biomass	5.49E-06	0.22%
Biorefinery: TCR	8.66E-05	3.41%
Biorefinery: GTL	5.43E-04	21.37%
Biorefinery: oil distillation	3.93E-07	0.02%
Biorefinery: electrooxidation	4.30E-04	16.91%
Utilization of waste products	2.77E-05	1.09%
Avoided use of liquid fuels	-2.40E-04	-9.42%
Avoided use of coke	-5.67E-04	-22.28%
Avoided use of other products	-4.13E-05	-1.63%
Total	**8.48E-04**	

Table 49. Life Cycle Impact Assessment of biomass processing: Human toxicity, cancer inorganics

Human toxicity, cancer inorganics	CTUh	% of total
Drying and pelletizing	1.94E-04	12.97%
Transport of biomass	5.35E-06	0.36%
Biorefinery: TCR	2.29E-05	1.53%
Biorefinery: GTL	3.55E-04	23.70%
Biorefinery: oil distillation	1.37E-07	0.01%
Biorefinery: electrooxidation	6.93E-05	4.63%
Utilization of waste products	2.72E-05	1.82%
Avoided use of liquid fuels	-2.32E-04	-15.51%
Avoided use of coke	-5.51E-04	-36.80%
Avoided use of other products	-4.00E-05	-2.68%
Total	**-1.49E-04**	

Table 50. Life Cycle Impact Assessment of biomass processing: Human toxicity, cancer organics

Human toxicity, cancer organics	CTUh	% of total
Drying and pelletizing	4.08E-04	38.96%
Transport of biomass	1.46E-07	0.01%
Biorefinery: TCR	6.37E-05	6.09%
Biorefinery: GTL	1.89E-04	18.04%
Biorefinery: oil distillation	2.56E-07	0.02%
Biorefinery: electrooxidation	3.61E-04	34.47%
Utilization of waste products	4.98E-07	0.05%
Avoided use of liquid fuels	-7.49E-06	-0.72%
Avoided use of coke	-1.59E-05	-1.52%
Avoided use of other products	-1.29E-06	-0.12%
Total	**9.97E-04**	

Table 51. Life Cycle Impact Assessment of biomass processing: Human toxicity, non-cancer – total

Human toxicity, non-cancer - total	**CTUh**	**% of total**
Drying and pelletizing	2.22E-02	28.19%
Transport of biomass	2.43E-04	0.31%
Biorefinery: TCR	2.54E-03	3.23%
Biorefinery: GTL	1.53E-02	19.50%
Biorefinery: oil distillation	1.58E-05	0.02%
Biorefinery: electrooxidation	6.86E-03	8.72%
Utilization of waste products	2.76E-03	3.51%
Avoided use of liquid fuels	-9.28E-03	-11.80%
Avoided use of coke	-1.81E-02	-23.04%
Avoided use of other products	-1.32E-03	-1.68%
Total	**2.12E-02**	

Table 52. Life Cycle Impact Assessment of biomass processing: Human toxicity, non-cancer inorganics

Human toxicity, non-cancer inorganics	**CTUh**	**% of total**
Drying and pelletizing	2.18E-02	28.12%
Transport of biomass	2.40E-04	0.31%
Biorefinery: TCR	2.50E-03	3.23%
Biorefinery: GTL	1.51E-02	19.49%
Biorefinery: oil distillation	1.55E-05	0.02%
Biorefinery: electrooxidation	6.73E-03	8.70%
Utilization of waste products	2.76E-03	3.56%
Avoided use of liquid fuels	-9.16E-03	-11.83%
Avoided use of coke	-1.79E-02	-23.07%
Avoided use of other products	-1.30E-03	-1.68%
Total	**2.08E-02**	

Table 53. Life Cycle Impact Assessment of biomass processing: Human toxicity, non-cancer organics

Human toxicity, non-cancer organics	**CTUh**	**% of total**
Drying and pelletizing	3.93E-04	32.68%
Transport of biomass	2.32E-06	0.19%
Biorefinery: TCR	4.54E-05	3.77%
Biorefinery: GTL	2.43E-04	20.22%
Biorefinery: oil distillation	2.80E-07	0.02%
Biorefinery: electrooxidation	1.25E-04	10.37%
Utilization of waste products	3.17E-06	0.26%
Avoided use of liquid fuels	-1.22E-04	-10.10%
Avoided use of coke	-2.51E-04	-20.86%
Avoided use of other products	-1.83E-05	-1.52%
Total	**4.22E-04**	

Table 54. Life Cycle Impact Assessment of biomass processing: Particulate matter

Particulate matter	**Disease incidences**	**% of total**
Drying and pelletizing	2.61E-02	27.38%
Transport of biomass	1.69E-04	0.18%
Biorefinery: TCR	4.21E-03	4.42%
Biorefinery: GTL	2.07E-02	21.70%
Biorefinery: oil distillation	1.61E-05	0.02%
Biorefinery: electrooxidation	2.50E-02	26.23%
Utilization of waste products	1.07E-04	0.11%
Avoided use of liquid fuels	-6.03E-03	-6.33%
Avoided use of coke	-1.21E-02	-12.68%
Avoided use of other products	-8.98E-04	-0.94%
Total	**5.72E-02**	

Table 55. Life Cycle Impact Assessment of biomass processing: Ionising radiation, human health

Ionising radiation, human health	**kBq U235 eq.**	**% of total**
Drying and pelletizing	1.56E+05	11.55%
Transport of biomass	7.24E+01	0.01%
Biorefinery: TCR	7.01E+04	5.21%
Biorefinery: GTL	3.30E+05	24.55%
Biorefinery: oil distillation	2.29E+00	0.00%
Biorefinery: electrooxidation	7.73E+05	57.46%
Utilization of waste products	7.14E+02	0.05%
Avoided use of liquid fuels	-4.57E+03	-0.34%
Avoided use of coke	-1.01E+04	-0.75%
Avoided use of other products	-1.02E+03	-0.08%
Total	**1.31E+06**	

Table 56. Life Cycle Impact Assessment of biomass processing: Photochemical ozone formation, human health

Photochemical ozone formation, human health	**kg NMVOC eq.**	**% of total**
Drying and pelletizing	3.50E+03	31.85%
Transport of biomass	2.01E+01	0.18%
Biorefinery: TCR	4.60E+02	4.19%
Biorefinery: GTL	2.49E+03	22.72%
Biorefinery: oil distillation	2.37E+00	0.02%
Biorefinery: electrooxidation	1.89E+03	17.25%
Utilization of waste products	8.26E+00	0.08%
Avoided use of liquid fuels	-7.75E+02	-7.06%
Avoided use of coke	-1.70E+03	-15.52%
Avoided use of other products	-1.26E+02	-1.15%
Total	**5.77E+03**	

5.2.3 Natural resources

Table 57. Life Cycle Impact Assessment of biomass processing: Land use

Land use	**Pt**	**% of total**
Drying and pelletizing	2.42E+06	9.66%
Transport of biomass	1.61E+05	0.65%
Biorefinery: TCR	1.05E+06	4.20%
Biorefinery: GTL	4.98E+06	19.92%
Biorefinery: oil distillation	1.17E+02	0.00%
Biorefinery: electrooxidation	1.15E+07	45.90%
Utilization of waste products	1.39E+04	0.06%
Avoided use of liquid fuels	-4.70E+06	-18.80%
Avoided use of coke	-1.85E+05	-0.74%
Avoided use of other products	-1.77E+04	-0.07%
Total	**1.52E+07**	

Table 58. Life Cycle Impact Assessment of biomass processing: Resource use, fossils

Resource use, fossils	**MJ**	**% of total**
Drying and pelletizing	7.34E+07	33.29%
Transport of biomass	3.87E+05	0.18%
Biorefinery: TCR	8.89E+06	4.03%
Biorefinery: GTL	4.37E+07	19.81%
Biorefinery: oil distillation	5.14E+04	0.02%
Biorefinery: electrooxidation	2.92E+07	13.26%
Utilization of waste products	4.19E+04	0.02%
Avoided use of liquid fuels	-1.76E+07	-8.00%
Avoided use of coke	-4.40E+07	-19.94%
Avoided use of other products	-3.21E+06	-1.45%
Total	**9.08E+07**	

Table 59. Life Cycle Impact Assessment of biomass processing: Resource use, minerals and metals

Resource use, minerals and metals	**kg Sb eq.**	**% of total**
Drying and pelletizing	8.60E-02	15.78%
Transport of biomass	1.85E-03	0.34%
Biorefinery: TCR	2.34E-02	4.30%
Biorefinery: GTL	1.24E-01	22.69%
Biorefinery: oil distillation	3.31E-05	0.01%
Biorefinery: electrooxidation	2.15E-01	39.44%
Utilization of waste products	1.95E-04	0.04%
Avoided use of liquid fuels	-5.87E-02	-10.79%
Avoided use of coke	-3.35E-02	-6.16%
Avoided use of other products	-2.52E-03	-0.46%
Total	**3.55E-01**	

Table 60. Life Cycle Impact Assessment of biomass processing: Water use

Water use	m3 world equiv.	% of total
Drying and pelletizing	6.52E+04	4.42%
Transport of biomass	3.28E+02	0.02%
Biorefinery: TCR	2.83E+04	1.92%
Biorefinery: GTL	6.19E+05	42.01%
Biorefinery: oil distillation	3.19E+00	0.00%
Biorefinery: electrooxidation	3.10E+05	21.00%
Utilization of waste products	-4.17E+05	-28.27%
Avoided use of liquid fuels	-2.60E+04	-1.76%
Avoided use of coke	-7.98E+03	-0.54%
Avoided use of other products	-7.00E+02	-0.05%
Total	**5.71E+05**	

5.3 Combined process

Environmental impacts of the combined process of phytoremediation and biomass processing presented in Table 61 have been calculated with regard to its functional unit "**processing 3 900 Mg of dry biomass**".

Table 61. Life Cycle Impact Assessment of phytoremediation combined with biomass processing

Impact category	Phyto-remediation	Biomass processing	Total	Unit
Climate Change - total	-3.69E+08	3.88E+05	**-3.68E+08**	kg CO2 eq.
Climate Change, biogenic	1.41E+04	2.53E+04	**3.94E+04**	kg CO2 eq.
Climate Change, fossil	5.23E+06	3.67E+05	**5.60E+06**	kg CO2 eq.
Climate Change, land use and land use change	-3.74E+08	-4.13E+03	**-3.74E+08**	kg CO2 eq.
Ozone depletion	2.35E-06	4.37E-05	**4.61E-05**	kg CFC-11 eq.
Ecotoxicity, freshwater - total	-5.91E+07	-1.36E+07	**-7.26E+07**	CTUe
Ecotoxicity, freshwater inorganics	-5.20E+07	-1.34E+07	**-6.53E+07**	CTUe
Ecotoxicity, freshwater organics	-7.11E+06	-1.96E+05	**-7.30E+06**	CTUe
Acidification	5.72E+04	6.22E+03	**6.34E+04**	mole of H+ eq.
Eutrophication, freshwater	2.00E+01	1.07E+01	**3.07E+01**	kg P eq.
Eutrophication, marine	2.88E+04	2.24E+03	**3.11E+04**	kg N eq.
Eutrophication, terrestrial	3.17E+05	2.36E+04	**3.41E+05**	mole of N eq.
Human toxicity, cancer - total	-5.82E-02	8.46E-04	**-5.74E-02**	CTUh
Human toxicity, cancer inorganics	-4.71E-02	-1.51E-04	**-4.72E-02**	CTUh
Human toxicity, cancer organics	-1.12E-02	9.97E-04	**-1.02E-02**	CTUh
Human toxicity, non-cancer - total	-8.90E+00	2.11E-02	**-8.88E+00**	CTUh
Human toxicity, non-cancer inorganics	-8.89E+00	2.07E-02	**-8.87E+00**	CTUh
Human toxicity, non-cancer organics	-1.12E-02	4.21E-04	**-1.07E-02**	CTUh
Particulate matter	1.14E+00	5.72E-02	**1.19E+00**	Disease incidences
Ionising radiation, human health	5.36E+04	1.31E+06	**1.37E+06**	kBq U235 eq.
Photochemical ozone formation, human health	8.08E+04	5.77E+03	**8.65E+04**	kg NMVOC eq.
Land use	-6.02E+10	1.52E+07	**-6.01E+10**	Pt
Resource use, fossils	7.13E+07	9.07E+07	**1.62E+08**	MJ
Resource use, minerals and metals	3.88E-01	3.55E-01	**7.43E-01**	kg Sb eq.
Water use	2.60E+07	5.71E+05	**2.66E+07**	m^3 world equiv.

6 INTERPRETATION OF RESULTS

Results of calculations presented in section 5 are discussed in section 6.1. Recommendations and plans for future work are presented in section 6.2.

6.1 Discussion of results

Results of Life Cycle Assessment for phytoremediation show that consumption of fuel is the greatest contributor to almost all impact categories. Only the use of fertilizers has a comparable or greater impact than the use of fuels in some categories (*Ozone depletion*, *Ionising radiation*), especially for the case of Serbian site, where the use of pesticides also has non-negligible impacts.

Although the results indicate a high positive impact of phytoremediation in the *Climate Change* category, they should be taken with a great dose of uncertainty. This is because the positive impact is associated with the change of carbon content in the soil (*Climate Change, land use and land use change* category), which is burdened with high uncertainty, as explained in section 4.1. Nevertheless, the impacts in the *Climate Change* category can be improved by carbon sequestration in the form of biomass residues that are left on the site after harvest. Quantification of this carbon (which will be potentially characterized by lower uncertainty) will be included in further iterations of the LCA.

The removal of contaminants from the soil has a beneficial impact on categories *Ecotoxicity* and *Human toxicity*. These beneficial impacts generally outweigh the adverse impacts caused by other groups of activities, resulting in an overall negative values of these environmental impact indicators.

It must be stressed that the presented results are based on inventory data from the first year of phytoremediation. It is expected that in the subsequent years, the rate of contaminants removal will decrease, which will reduce the positive impacts in *Ecotoxicity* and *Human toxicity* categories. However, at the same time, the biomass yield may increase, potentially improving the environmental impacts of the entire process. Additionally, for scaled up phytoremediation sites, the specific fuel consumption for agricultural activities is expected to be lower.

The first approach to the LCA of biomass processing followed the base case scenario, which assumed that 100% of the syngas is directed to GtL, external source for hydrogen is used to facilitate this process, and no recirculation of heat or mass streams takes place. Hence, the quantitative results presented in this deliverable should be interpreted with caution as they present the pessimistic case with high input of external energy required.

For the biomass processing subprocess, three groups of activities negatively stand out in the LCIA: Drying and pelletizing, GtL and Electrooxidation. This is a result of high consumption of heat and electric energy in these activities, and in the case of GtL also the use of external hydrogen. Even though the avoided use of fossil fuels, especially coke, results in reductions of greenhouse gas emissions, they are outweighed by the emissions associated with energy consumption in the biorefinery and, as a result, the overall impact of the biorefinery in the field of *Climate change* is adverse. In fact, the only categories in which the biorefinery gets a positive environmental score, are *Ecotoxicity, freshwater* and *Human toxicity, cancer inorganics*.

LCIA of averaged phytoremediation combined with biomass processing shows positive impact of the proposed technology on the *Ecotoxicity* and *Human toxicity* impact categories, as well as *Land use*. However, the environmental impacts in all other categories (except for the uncertain *Climate Change, land use and land use change* category) are adverse. This is a direct consequence of negative energy balance of the system and assumed utilization of non-renewable energy sources for driving the biorefinery (quantified in the *Resource use, fossils* impact category).

6.2 Recommendations and future work

In the next steps of the project, optimization of the biorefinery concept should be carried out in tight cooperation with business model plans. Selected scenarios identified as the most promising can be then evaluated using LCA approach proposed hereby, and a sensitivity analysis should allow estimating conditions that will ensure positive environmental impact of the phytoremediation-biorefinery system.

This first overview of the biorefinery concept points towards a few potentially crucial aspects in the operation of the system:

- The magnitude of environmental impacts of biorefinery is mainly determined by the source of energy used for driving the processes. In the current analysis, the most widely available, mostly non-renewable sources of energy have been assumed. Changing the energy sources to renewable ones could greatly improve the environmental impacts of biorefinery.
- Following the business model, it was assumed that biomass is actively dried using heat of (by default) non-renewable origin. In practice, the harvested biomass can be just left at the field to dry using solar energy. It would greatly improve the environmental impacts, because currently “Drying and pelletizing” is the greatest contributor to the *Resource use, fossils* category. This variant will be analysed in further iterations of LCA.
- The possibilities of heat recirculation in the biorefinery, which would reduce the use of external energy sources, will be highly dependent on the biorefinery setup. Each scenario might result in a quite different heat demand/generation outcome.
- Conversion of the total stream of syngas requires large amount of excess hydrogen. Fossil-fuel based hydrogen will impair the environmental footprint of the system, while production of hydrogen by electrolysis will require high energy input.
- The unreacted hydrogen from the GtL could be recirculated, thus needing additional equipment and energy, yet reducing the stream of required external hydrogen. Otherwise it will end up in the tail gas, resulting in its high calorific value. Combustion of this gas could provide heat needed in other biorefinery processes.
- The fate of CO_2 in the syngas will affect the technical aspects of the biorefinery concept, thus influencing the outcomes of economic and environmental analyses. Sequestration of CO_2 will generate additional waste streams and will increase energy consumption; utilization of CO_2 in GtL requires additional H_2 and might require additional conversion step such as reversed water gas shift reaction; recirculation of CO_2 (e.g. to the TCR reactor) might affect the product distribution.
- TCR process carried out under inert atmosphere requires providing N_2, and furthermore, N_2 is present in the syngas and needs to be separated, or otherwise, it will increase energy consumption of the compressor and also possibly affect the operation of the GtL unit.

Results of the biorefinery inventory suggest that the abovementioned aspects should be considered while developing future scenarios. It seems that the main focus should be paid to the syngas processing – percent of the syngas directed to the GtL unit, the arrangement of N_2, H_2 and CO_2 streams, and the parameters of the GtL process itself.

Some other hypothetical solutions might be worth consideration, namely:

- High pressure electrolysis for external hydrogen production would decrease energy consumption of the gas compression required before the GtL unit.
- TCR operation with CO_2 instead of N_2 would eliminate non-usable carrier gas and allow for CO_2 recirculation. However, this modification would fundamentally change the TCR process.
- High pressure pyrolysis reactor would create compressed syngas and allow to eliminate the compression unit, yet it will again fundamentally change the biomass conversion process.

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