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# **Environmental Aspects in the Life Cycle of Liquid Biofuels with Biocomponents, Taking into Account the Storage Process**

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Izabela Samson-Bręk, Barbara Smerkowska and Aleksandra Filip

Additional information is available at the end of the chapter

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## **1. Introduction**

Environmental Life Cycle Assessment is a technique designed to assess the environmental risks associated with the product system or activity, either by identifying and quantifying the energy and materials used and the waste introduced into the environment, as well as the environmental impact of such materials, energy and waste. The assessment relates to the whole life cycle of the product or activity from the mining and mineral processing, product manufacturing process, distribution, use, re-use, maintenance, recycling up to the final disposal and transportation. LCA directs the study of environmental impact of the product system to the area of the ecosystem, human health and the resources used.

Results of studies on LCA were first presented by Harold Smith during the World Energy Conference in 1969. Interest in the usefulness of LCA was shown by Coca-Cola which commissioned an LCA of its beverage packaging products. On the other hand, theoretical foundations of LCA methodology were established as late as in 1990. Because of the growing interest in methods for LCA, works were commenced by the Society of Environmental Toxicology and Chemistry (SETAC) and ISO to harmonize and standardize the LCA methodology. The effort provided a definition of LCA and a number of standards (the series ISO EN 14040).

Even for same products, LCA can be performed at different levels of detail. Business purposes and executive decisions in management are well served by screening LCA (the shortest and simplest variant) or by simplified LCA; the latter is used, for instance, in decision-making processes concerning product development or in communication strategies. Detailed LCA is

used for a full LCA and for comparative studies of products. It is based on detailed original data, obtained primarily by direct measurements, analyses, discussions, while also using latest literature data and statistical information after verification of their reliability. In R&D, the typical levels are the simplified LCA and detailed LCA.

In Poland, LCA remains to be a rather novel method in environmental management. It is used mainly for R&D purposes and is developed in R&D centers. In the light of the requirements regarding minimization of the adverse environmental impact of the fuel industry, imposed by the EU legislation, LCA seems a useful tool to fulfill such requirements. It may encompass the whole life cycle of a fuel, from the mining of raw materials, all the way through its manufacturing, use, and processes involved in the handling of those fuels which are below the applicable standards [2].

The use of LCA in the fuel industry enables the realization of and indicates relationships between human activities and their consequences for the environment. Moreover, it is an important source of information in making decisions intended to minimize the adverse impact of fuel production technology on the environment and to improve its condition. LCA enables identification of the processes of technology with the highest consumption of energy and highest emissions, as well as reduction of the costs of energy and raw materials, and efficient management of waste arising in technological processes.

This chapter presents Life Cycle Analysis as one of the methods enabling assessment of the environmental impact of the production of engine fuels and biofuels, especially their storage. A comparison of LCA and WtW analyses is made, and computer software is compared in the aspect of capabilities and justification for its use in assessing the environmental impact of the manufacturing and use of fuels and biofuels. The respective steps of LCA as well as the requirements and rules of assessment are discussed, taking into account their impact on the final result of LCA.

## 2. Relations between LCA and WTW

As pointed out earlier in this chapter, LCA enables the assessment of environmental risks over the whole life cycle of a product or process, starting from the mining and processing of raw materials, all the way through the manufacturing, distribution, use, re-use, maintenance, recycling, and final disposal and transportation. LCA directs the study of environmental impact of a product system to the area of the ecosystem, human health and the resources used [1].

Even for same products, life-cycle assessment may have different levels of detail, depending on the addressee of the results of the assessment and on its intended use. Essentially, three variants of LCA exist [3, 4]:

- *Screening LCA* – typically used within a single entity but also in circumstances requiring a fast analysis or low budget; screening LCA uses approximated secondary data from existing

databases or statistical sources. a sensitivity analysis is recommended in this LCA variant in order to establish the actual impact of the results obtained on the key issues of the analysis;

- *Simplified LCA* – used in decision-making processes concerning product development and in communication strategies. Input data for the analysis may originate from existing databases but they should be supplemented with current literature data and with primary information obtained from suppliers, manufacturers or other product chain participants, or from direct discussions and measurements. A sensitivity analysis is indispensable to correct essential assumptions, if required;
- *Detailed LCA* – used for a full LCA of products and for comparative studies of products. It is based on detailed primary data, obtained by means of direct measurements, studies, analyses or discussions but also on latest literature data and statistical information after verification of their reliability. According to ISO EN 14040, an independent reviewer ought to be included in every step of the assessment process. It is necessary to describe all procedures, instances where data are incomplete, to carry out a thorough sensitivity analysis and justify choices.

A Well-to-Wheel analysis (from the fuel production to the energy that drives the vehicle) is a variant of LCA, dedicated to the assessment of the environmental impact of the life cycle of the production and use of transport fuels and vehicles. The WtW analysis is commonly used in assessing the consumption of energy or emissions of greenhouse gas (GHG) in the entire life cycle of a fuel, as well as for assessment of energy efficiency. The following variants of WtW are possible:

- „well-to-station” WtS (from fuel production to the filling station);
- „well-to-tank” WtT (from fuel production to the tank);
- „station-to-wheel” StW (from the filling station to the energy that drives the vehicle);
- „tank-to-wheel” TtW (from tank to the energy that drives the vehicle);
- „plug-to-wheel” PtW (from plug to the energy that drives the vehicle).

Relationships between LCA and WtW are shown in Figure 1.

The methodology of LCA and WtW according to ISO series 14040 [5, 6], involves four phases:

- i. Goal and Scope definition;
  - ii. Life Cycle Inventory (LCI);
  - iii. Life Cycle Impact Assessment (LCIA);
  - iv. Life Cycle Interpretation.
- i. Goal and Scope definition

The initial phase of LCA; decisions made in this phase determine the whole analysis. It is essential to precisely formulate the goal of LCA, justify its choice, specify the way the results of LCA are going to be used, and indicate the final user. The goal of LCA is defined in ISO EN 14040: the

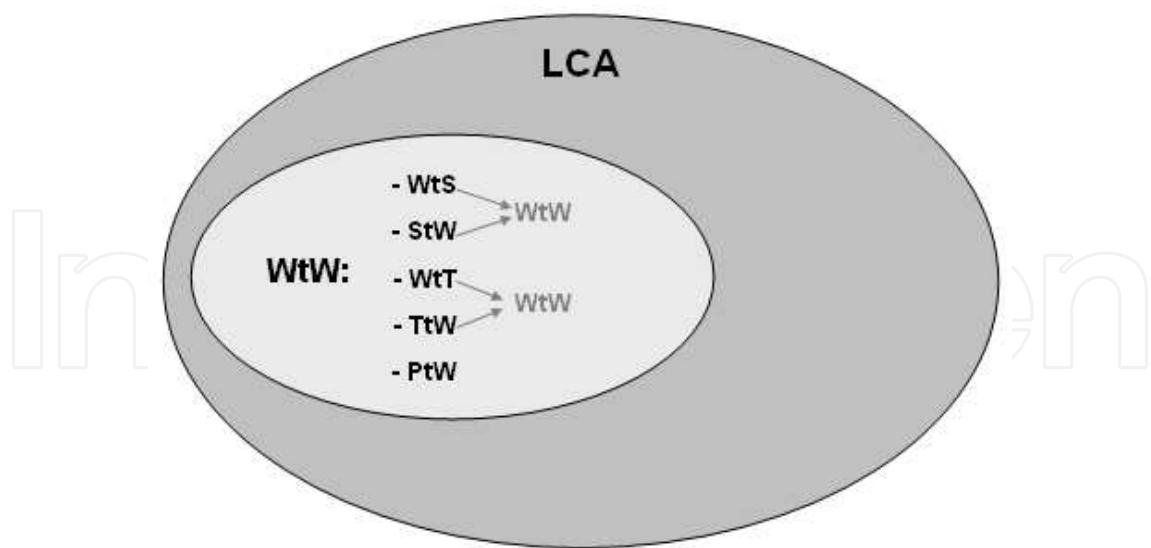


Figure 1. Correlation between LCA and WtW

goal ought clearly to indicate the intended use, the reasons for carrying out the LCA, and the potential user.

The scope of LCA will result from the established goal and ought to specify in detail the functions and the product system boundaries. The notion of system boundaries is understood as the contact area between the product system and the environment or other product systems. The system boundaries determine the framework of LCA. A function (or functional unit) is the quantitative effect of the product system, used as a reference unit in LCA. It is the task of the functional unit to provide a plane of reference for standardization of input and output data based on the mathematical approach [4].

As mentioned earlier in this chapter, WtW analyses are merely a variant of LCA, one applied in assessing the environmental impact of the production and use of fuels and vehicles. The scope of LCA is much broader and concerns freely selected products (Table 1).

The system boundaries for WtW comprise, first of all, production and distribution of fuels, and emissions caused by their combustion in the vehicle's engine. In contrast, the system boundaries for LCA comprise processes, making up the entire life cycle of a product (Table 1).

Life cycle analysis dedicated to transportation comprises usually three phases: production, use, and recycling, as well as production and distribution of the appropriate fuel. Production of the infrastructure, both in LCA and in WtW analyses, is outside the system boundaries because of its lesser importance and lower impact on the outcome of the analysis.

ii. Life Cycle Inventory (LCI)

In the second phase, called Life Cycle Inventory (LCI), input/output data (concerning the inputs/outputs to/from the environment) are collected and analyzed. Such data are collected for every single unit process which is specified in a product system. The product system is

understood as a set of materially and energetically connected unit processes which fulfill one or more specific functions. The unit process is the smallest part of the product system, for which data are collected when carrying out a life cycle analysis.

Specifications are prepared for the input/output quantities of materials and energy (side products, emissions, waste) to/from a given process. The LCI results are typically in the form of inventory tables, presenting quantitatively the consumption of natural raw materials, intermediate products, and generated waste. Important steps in data collecting include checking them for completeness and their validation.

In the case of WtW, the input data usually concern GHG emissions (mainly CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub>), consumption of energy, and energy efficiency (Table 1).

### iii. Life Cycle Impact Assessment (LCIA)

The goal of the Life Cycle Impact Assessment (LCIA) is to establish the environmental relationships between all inputs/outputs covered by the LCA and to assess environmental impact.

During LCIA, the results of LCI are grouped into the appropriate categories of environmental impact based on the adopted environmental priorities taking into account local/regional conditions. Such classification consists in allocating the LCI results obtained by data inventorying into the respective categories of assessment of environmental impact [5]. A single result of LCI may be classified into more than one category of environmental impact. The way in which the single result is assigned into the appropriate category depends on the method of life cycle impact assessment and on the adopted goal of the analysis. The respective environmental impact categories are assigned weight coefficients, depending on their respective degrees of impact on the environment. This enables an assessment of the extent of impact of the various environmental loads forming the set of inputs/outputs in a given production system, and helps find out in which steps of the life cycle such impact takes place.

Owing to the use of available software, dedicated to LCA analysis, the classification process is automated. The LCI results are allocated into the appropriate categories of impact on the basis of lists of substances included in a software database and belonging with the calculation methods used.

LCIA comprises two groups of elements [5]:

- **compulsory elements**, including:
  - choice of category of the assessment of environmental impact, category indicators and characterization models;
  - allocation of LCI results to the respective categories of impact (classification);
  - calculation of the value of the category indicator (characterization).
- **optional elements**, which include:
  - standardization;



- grouping;
- weighting.

In the life cycle analyses of products based on the LCA methodology, it is possible to choose various categories of the assessment of environmental impact, depending on the goals and assumptions of the analysis and the analyzed product type. By contrast, impact categories in WtW concern, in the first place, emissions of GHG and air pollution.

iv. Life Cycle Impact Interpretation

Interpretation is the final phase of LCA. Its chief goal is to review and contemplate the results, make sure they are complete, coherent, and useful to the goal and scope. In this phase, final conclusions are formulated, limitations are explained and guidelines on how to reduce environmental impact are provided.

LCA enables management in manufacturing processes and their modification in the aspect of reduction and rationalization of the use of fuels and raw materials. That is why the Abiotic Depletion Potential (ADP) factor has been introduced in this analysis. ADP is based on the concentration of resources globally and on the rate of de-accumulation and is established for the mining of every type of fossil resources. Moreover, the collected information is processed to express the ratio of the quantity of resources used to the quantity that remains in nature, in order to achieve the required characterization factor.

Owing to the introduction of “ozone depletion” and “change of climate” factors, the LCA technique enables reduction of negative environmental impact for products, mainly by the exact analysis of carbon footprints and determination of the extent of reduction of carbon dioxide emission.

WtW	LCA
<b>Goal:</b> assessment of the environmental impact of the production and use of fuels and vehicles	<b>Goal:</b> assessment of the environmental impact of the production and use of any selected products and processes
<b>Scope:</b> production and distribution of fuels, emissions caused by fuel combustion in vehicle’s engine	<b>Scope:</b> all processes making up the whole life cycle of a product
<b>Input data:</b> emissions of GHG (mainly CO <sub>2</sub> , N <sub>2</sub> O in CH <sub>4</sub> ), consumption of energy, energy efficiency	<b>Input data:</b> all energy and material flows, waste and emissions (dust and gas) into water, air and soil
<b>Impact categories:</b> it is possible to choose between various categories of assessment of the environmental impact, depending on the goals and assumptions of analysis and on product type	<b>Impact categories:</b> impact categories mainly for emissions of GHG and air pollution
<b>Standardization:</b> no established methodology	<b>Standardization:</b> analyses according to ISO EN 14040, 14041, 14042, 14043

Table 1. Main differences between LCA and WtW analyses

### 3. Programs for environmental impact assessment

#### 3.1. Programs for LCA analysis

There are more than 20 well known LCA software products in the international market. The first task faced by the potential user is to choose the proper tool for their particular problem. The choice has to be done based on a combination of the user's financial capabilities and functional requirements, on a case by case basis. The leading programs, as listed by subject, are the following:

- SimaPro 7 (and the recently released version SimaPro 8) by PRe Consultants, Netherlands;
- GaBi 4 (Ganzheitliche Bilanzierung – holistic balancing) by PE Europe GmbH and IBP University of Stuttgart;
- Umberto by the Institute for Environmental Informatics, Hamburg;
- GEMIS (Global Emission Model for Integrated Systems) by Oeko-Institut. GEMIS is a LCA program and database for energy, material, and transport systems;
- IDEMAT by Delft University of Technology. IDEMAT is a tool for material selections in the design process;
- CMLCA (Chain Management by Life Cycle Assessment) by Centre of Environmental Science (CML) – Leiden University;
- Open LCA – open source software;
- Team by Pricewaterhouse Coopers Ecobilan Group;
- Wisard (Waste – Integrated Systems Assessment for Recovery and Disposal) by Pricewaterhouse Coopers Ecobilan Group;
- GREET by Argonne National Laboratory US;
- Solid Works by Solid Works Sustainability;
- SPOLD Data Exchange Software by The Society for Promotion of Life-cycle Assessment;
- BEES (Building for Environmental and Economic Sustainability) by the National Institute for Standards and Technology (NIST) Building and Fire Research Laboratory;
- The Environmental Impact Estimator – by the ATHENA Sustainable Materials Institute;
- LCAPIX by KM Limited;
- Windchill LCA by PTC.

Two commercial programs: SimaPro and GaBi, the universal LCA software for products and services, are the most widely used ones. Being professional LCA software tools, both SimaPro and GaBi use databases which are regularly updated by their respective publishers. What is important to mention-LCA software is only a kind of interface with which to upload and



process data. The other essential part of the software are the inventory databases as well as impact assessment methods. One of the most extensive and well known databases is Ecoinvent, with its latest 3.0 version [<http://www.ecoinvent.org/database>]. Containing more than 4 000 inventories in different categories (e.g., energy, biofuels and biomaterials, transport, chemical products, waste treatment, building materials, agriculture and other ones) is one of the most comprehensive international LCI (Life Cycle Inventory) databases. The main data validity area is Western Europe and Switzerland, though it contains data also from other regions of the world. The database is included e.g., in SimaPro, GaBi, Umberto or IKE programs, and is continuously updated.

SimaPro, invented by the Dutch company PreConsultants, is a robust and thoroughly tested LCA tool, based on reliable, scientific data. The latest version of SimaPro (number 8) contains additionally water footprinting assessment and a much larger Ecoinvent 3.0 database. SimaPro contains multiple impact assessment methods as well as several inventory databases and approx. 10 000 processes available. The added value of this tool is the editing capability and expanding databases with own data without limitation and also adjusting existing and creating new impact assessment methods. This makes it a flexible tool, suitable for complex life cycles comparison and environmental performance analyzes. SimaPro offers a full review of the potential impact of the product. It is able to determine the key environmental performance indicators (KePI) used for determining and assessment of the execution of adopted objectives. The KePI approach is fundamental in EU policy, as key indicators are easily understood and managed. Being a commonly used software, it enables analytical results to be shared with other researchers or companies throughout the world.

GaBi is a system based on three simple concepts: plans, processes, flows. The plan represents the analyzed life cycle; the processes apply to the plan, representing the actual steps occurring in real life; the flows connect the processes and represent the material and energy balance in the system. As GaBi can be integrated with some databases, it is possible to use predefined data for creating one's own models. The tool enables visual analysis: where the biggest impacts occur, and what are the largest opportunities for improvements in the processes. It is also possible to compare how the system's behavior is affected by changes implemented in flows – alternative models show how the changes affect the environmental, economic and social aspects in the system. GaBi has the option of easily creating the reports, e.g., concerning “if scenarios” as well as Environmental Product Declaration and ISO compliance reports. GaBi databases contain large internally consistent LCI datasets available (over 7 200 datasets). The database covers all essential fields of energy and material production as well as transportation, its contents can be extended in response to any client-specific demand. It can be combined with the Ecoinvent database as well. GaBi can be used in designing products with more environmentally friendly components (with lower GHG emissions and a reduced water footprint and waste use).

With SimaPro and GaBi it is possible to create complex models and use the software in highly complicated and expert analyses. More advanced analyses within SimaPro and GaBi, such as variation of parameters (comparing and modeling different scenarios), sensitivity analysis and

Monte Carlo simulations with uncertainty analysis giving the level of standard deviations, are possible.

Beside these two most popular tools, there are also other software products. Some of them are open source software products, such as Open LCA. It is a modular software for life cycle analysis and sustainability assessments. But the important thing when considering the use of free software is that no process data are included. Therefore, it is necessary to use external databases which is an extra cost [7].

The use of various software capabilities also depends on the region. For example, GREET, published by the Argonne National Laboratory, is a popular software product in the USA. It is sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) and, therefore, free of charge. The software is used for GHG, regulated emissions, and energy use in transportation modeling. It is dedicated to transport issues, enabling the assessment of energy and emission impacts of advanced vehicle technologies and new transportation fuels [8]. This kind of software is convenient for WtW analyses.

Some LCA tools are more specific LCA software programs; one of them is EASEWASTE (Environmental Assessment of Solid Waste Systems and Technologies) focused on waste management system analyses. It is an LCA tool, developed at the Technical University of Denmark, modeling "resource use and recovery as well as environmental emissions associated with waste management in a life-cycle context. The model is set up for municipal waste but can also be used for other waste types" [9]. Recently, its successive form has been released under the name EASETECH – Environmental Assessment System for Environmental Technologies.

The general rule for choosing the proper tool for LCA modeling is the goal and scope of analysis, the target group of the results of analysis, and financial capabilities. Moreover, it is based on individual choice of the most intuitive software interface, the databases contents and possibility of their expanding and personalization. Using a model always involves simplification of reality, which causes distortion. The key requirement for any modeling tool is to minimize such distortions. \*\*

### **3.2. BIOGRACE as a tool for environmental analysis of biofuels**

BIOGRACE (version 4) is one of the most useful tools, dedicated to the calculation of greenhouse gas emissions which accompany the manufacturing of biofuels, available in Europe at present. The calculator has been developed by an international consortium as part of the project named BIOGRACE "Harmonized Calculations of Biofuel Greenhouse Gas Emissions" [10]. The calculator fully complies with the methodology for assessing greenhouse gas emissions caused by the production and use of transport fuels, biofuels, and biofluids, referred to in Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources, Annex V, Part C (RED). It was meant to be a scientific tool facilitating the implementation of those provisions of the Directive, concerning sustainable production of biofuels [11].

The BIOGRACE calculator is a tool which, at present, allows only the calculation of the emissions of greenhouse gases accompanying the production of 1<sup>st</sup> generation biofuels. As regards the biofuels obtained from lignocellulose raw materials and waste, the calculator can be used as well, although a number of assumptions are required, potentially making the final result too uncertain. Moreover, it is necessary to introduce own input data in the analysis.

According to the methodology referred to in Annex V, the total greenhouse gas emission in the life cycle of fuels and biofuels is made up of the following processes [11]:

- total emissions due to the use of fuel;
- emission due to the mining/cultivation of raw materials;
- annual emission caused by variations in the quantity of carbon stock due to changes in land use;
- emission due to processes of technology;
- emission due to transportation and distribution;
- the extent of reduction of emissions, caused by the accumulation of carbon stock in soils due to improvements in agricultural economy;
- reduction of emissions due to carbon dioxide capture and storage in deep geological structures;
- reduction of emissions due to carbon dioxide capture and substitution;
- reduction of emissions due to an increased production of electrical energy by co-generation.

According to the methodology recommended by the European Commission, emissions caused by the production of machinery and equipment are not taken into account in RED. The production of machinery and infrastructure on the total result of the life cycle impact assessment usually has a minimum effect [11].

The BIOGRACE calculator enables the assessment of agricultural emissions of GHG as well as emissions and reductions of emission in the entire life cycle of biofuels per 1 MJ of manufactured biofuel. The following steps are included in calculating GHG in the respective biofuel production pathways: cultivation of raw material, process of technology, transportation and distribution. Emissions are assessed for three principal greenhouse gases: CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O. It also is possible to show aggregate values of emissions, as expressed in carbon dioxide equivalent. When interpreting the results of analysis, it should be remembered that BIOGRACE does not take into account all types of emissions, or types of impact other than emissions of GHG (such as acidification, eutrophication, emission of solids etc.).

BIOGRACE enables the calculation of emissions of GHG which accompany the cultivation of 8 plants which are substrates for making biofuels, and 22 pathways for production of biofuels (Table 2) [11].

Substrate	Biofuel production pathway
1. wheat	1. ethanol from sugar beet
2. sugar beet	2. ethanol from wheat (not specified technological fuel)
3. corn	3. ethanol from wheat (brown coal as a process fuel in heat-and-power plants)
4. rape	4. ethanol from wheat (natural gas as a process fuel in conventional boilers)
5. sunflower	5. ethanol from wheat (natural gas as a process fuel in heat-and-power plants)
6. palm oil	6. ethanol from wheat (straw as a process fuel in heat-and-power plants)
7. soy	7. ethanol from corn made in the EC (natural gas as a process fuel in heat-and-power plants)
8. sugar cane	8. ethanol from sugar cane
	9. biodiesel from rapeseed
	10. biodiesel from sunflower
	11. biodiesel from soy
	12. biodiesel from palm oil (not specified technology)
	13. biodiesel from palm oil (technology with methane capture in the oil mill)
	14. biodiesel from spent vegetable or animal oils
	15. hydrorefined vegetable oil (HVO) from rapeseed
	16. hydrorefined vegetable oil (HVO) from sunflower
	17. hydrorefined vegetable oil (HVO) from palm oil (not specified technology)
	18. hydrorefined vegetable oil (HVO) from palm oil (technology with methane capture in the oil mill)
	19. pure vegetable oil from rapeseed
	20. biogas from organic municipal waste as compressed natural gas
	21. biogas from wet manure as compressed natural gas
	22. biogas from dry manure as compressed natural gas

**Table 2.** Substrates and biofuel production pathways included in the BIOGRACE calculation tool

The BIOGRACE methodology for assessing greenhouse gas emissions in the step of cultivation of raw materials comprises the following [11]:

- production of seed/seedling material;
- fertilization with nitrogen (N);
- fertilization with phosphorus ( $P_2O_5$ );
- fertilization with potassium ( $K_2O$ );
- fertilization with calcium (CaO);
- plant protection agents;
- consumption of fuels when carrying out all the necessary field works;
- field emissions of  $N_2O$ ;

- annual emissions caused by changes in the quantity of carbon stock due to changes in land use;
- emissions caused by the soil accumulation of carbon stock due to improvements in agricultural economy.

Furthermore, the BIOGRACE calculator enables the use of standard values of emissions, specified in the Directive Annex V, as well as the introduction of values provided by other sources, such as studies or own estimates. Emissions which accompany the production of nitrogen-based fertilizers are an example of the application of non-standard values for calculations. BIOGRACE assumes that a standard value of emission for conditions prevailing in Europe is  $5880.6 \text{ g CO}_2_{\text{eq}}/\text{kg N}$ . However, the works carried out by IUNG State Research Institute (Institute of Soil Science and Plant Cultivation) in Puławy, Poland, indicate that in Poland, emission accompanying the production of nitrogen-based fertilizers is much lower: just  $3414.2 \text{ g CO}_2_{\text{eq}}/\text{kg N}$  [12]. Since the use of a value which is prevailing in Poland will result in a lower total emission caused by the production of raw material and of the biofuel itself, such lower emission value is more preferable in the calculations [13].

## 4. The quality of results and the methodological assumptions

### 4.1. Goal, scope and system boundaries

LCA analysis approach has always to be related to goal and scope as well as the analysis target group. The intended application has to be defined. Typical applications can be as follows [16]:

- Comparing products having the same function (usually used in marketing or regulation);
- Identifying environmental hot-spots in product life cycle;
- Identifying possibilities of improvement of product or its production process;
- Communication to customers.

A product system is a collection of materially and energetically connected unit processes which perform one or more defined functions and reflect the life cycle of a product [5]. A product system in LCA is typically understood as its production line. Established on this basis are system boundaries, defined as an “interface between a product system and the environment or other product system”. System boundaries determine the unit processes which are included in the LCA analysis. The choice of unit processes ought to result from the goal, as established previously, while criteria of choice of the adopted system boundaries ought to be clearly and precisely established. It is important to make a contribution analysis and establish whether all highest-load processes have been taken into account. Typically, about 10 processes are of significance to the results of an analysis. Decisions on which processes should be included in the analysis or which ones are not important enough can be taken using the cut-off method for processes of which the contribution, for instance, in the consumption of energy or materials does not exceed a certain value (percentage or quantity). As a matter of fact, subjective choices



are inherent in this type of analysis, therefore, one ought to check whether the results of analysis and the conclusions depend on the choices made. One of the applicable methods is to make calculations after modifying the assumptions (sensitivity analysis). In a sensitivity analysis, it is possible, for instance, to change a data source (process or database), compare results for different values of parameters (such as distance, type of transportation, waste recycling method), allocation (mass, economic) or absence of allocation, assumption, and the impact assessment method. If the results of analysis have changed after such modification (for instance, Process A is better than Process B or vice versa), then the fact ought to be commented on and explained.

Product life cycles are usually complex. It is then essential to maintain balance between complexity (high costs) and simplification (lower costs, possibility of providing the results in an easily understandable way). Depending on the goal of analysis, the scope can be reduced, focusing on e.g., only energy or mass or CO<sub>2</sub> emission issues. Another potential solution is to use the KePI (Key environmental Performance Indicators) approach, based on identification of key parameters determining major impact.

For a given LCA analysis, the geographic boundaries depend on the assumptions of a specific analysis/project. They can be established at the local, national, regional or global level. If the geographic region of the analysis covers a given country, it is permissible in certain instances (e.g., data concerning means of transport) to use average data, for instance, for the region of Europe. However, it is always necessary to carefully examine the possibilities to use average data, for instance, in the case of production of electrical energy, differences in division by country are essential (energy mix) and may lead to understated or overstated results.

As regards areas of technology, data concerning innovative processes (such as evaluation of new processes of technology) ought to originate from actual research works dedicated to a given process. In the case of non-innovative, previously used processes it is permissible to use data from literature sources.

#### **4.2. Input data**

According to ISO EN 14040, in publicly available comparative analyses, it is necessary to establish data quality requirements. The scope of uncertainty of the input data will be reflected both in the results of analysis and in the method for their interpretation.

The quality of input data for an analysis is established on the basis of such parameters as: time interval, geographic region, area of technology, precision, completeness, representativeness, consistency, reproducibility, data source, and uncertainty. The parameters concerning data quality, described in ISO EN 14040, are characterized below:

- time interval of data: actual data ought to originate during the project execution; departures by several years are permissible for literature data if it is impossible to acquire real-time data;



- geographical coverage: data ought to originate from studies carried out in the territory of a given country; in certain cases (such as data concerning means of transport) averaged data for the region of Europe are permissible;
- area of technology: data concerning processes of technology ought to originate from studies conducted or from operating facilities; for processes and technology for which it is not possible to acquire real-time data, it is permissible to use literature data;
- precision: data ought to be characterized by as high a precision as possible;
- completeness: data ought to be as complete and as accurate as possible;
- representativeness: data ought to be representative in as much as possible;
- consistency: qualitative assessment of how uniformly the study methodology is applied to the various components of the analysis;
- reproducibility: data ought to originate from suitably documented studies to enable their reproduction and verification, if required;
- data source: data ought to originate from own studies or actual data, obtained in an operating facility, in the first place; from the point of view of the results of analysis, such data have the highest value; it is permissible under certain circumstances to use literature data or data from available databases, including those originating from the SimaPro software, which is used for LCA analyses;
- uncertainty: data ought to be characterized by the least possible uncertainty; moreover, any uncertainty concerning the data ought to be clearly formulated.

In LCA analyses carried out for scientific purposes, it is important to establish the scope of uncertainty of input data and, on this basis, to carry out the Monte Carlo uncertainty analysis.

#### 4.3. The choice of LCA method — Impact categories

In choosing impact categories and LCA method, one ought to keep in mind the goal and scope of analysis in the first place. When comparing the environmental impacts of the life cycles of biofuels and fossil fuels, they ought to be considered in similar impact categories (e.g., global warming). Moreover, system-specific categories ought to be taken into account: in the case of biofuel production, it will be, e.g., the use of land for cultivation of energy plants. A typical set of categories in which the environmental impact of a product system is calculated (method: Ecoindicator 99 from SimaPro) is shown below:

- Carcinogens;
- Respiratory organics;
- Respiratory inorganics;
- Climate change;
- Radiation;

- Ozone layer;
- Ecotoxicity;
- Acidification/Eutrophication;
- Minerals
- Fossil fuels;
- Land use.

Because SimaPro is a leading tool for LCA analyses globally, the criteria of choice of the most suitable method for the analysis have been characterized on the basis of SimPro. The tool offers a dozen or so methods for life cycle impact assessment and the differences between them are significant. Therefore, when choosing the suitable method, it is necessary to clearly state the priorities for the specific LCA analysis. To make it easier to choose the life cycle impact assessment method, SimaPro has the "Method selector" tool. It helps understand the major differences between the various life cycle impact assessment methods and select the most suitable method, depending on the assumed goal and scope of analysis of LCA. Selection of the suitable method using the tool include the following aspects: result presentation as single score (numerical value), weighting set, time perspective, geographic coverage, accuracy of the life cycle impact assessment method and the impact categories considered in the method.

Some methods enable presentation of results in the form of single scores. On the other hand, according to ISO EN 14040, this way of presentation of the results, as results of comparative analyses which are going to be made public, should be avoided because they are too subjective, and simplifications are significant. In public, scientific papers, mainly midpoint methods are used as they are more scientifically certain. In that case, the life cycle impact assessment method is preferable, being one that enables presentation of results as indicators which are characterized separately for every impact category. Also weighting (that is, the allocation of weight to the respective impact categories) is not permissible in life cycle analyses which are presented in public [6]. In such cases, the way it was carried out has no effect on the method selection. Weighting or endpoints can be shown in business to business analyses, but not in public ones. When comparing some results and methods – it is not methodologically correct to compare endpoint and midpoint methods, as the results are shown in different ways, also of high importance is comparing two products only when the system boundaries and all the life cycle stages are the same.

When selecting the suitable life cycle impact assessment method, it is necessary to decide whether the selected method is going to cover a short-or a long-term horizon. In long-term methods, more emphasis is placed on those substances which persist in the environment for many years (like heavy metals). Since human activities have a long-term environmental impact by nature, the approach often seems to be the most appropriate one.

In selecting the suitable method, its complexity ought to be considered as well: the simpler the method, the more general results are provided. Recently developed methods, based on latest scientific accomplishments, are much more complex and require more accurate data; on the other hand, the results they provide are much more reliable and precise.

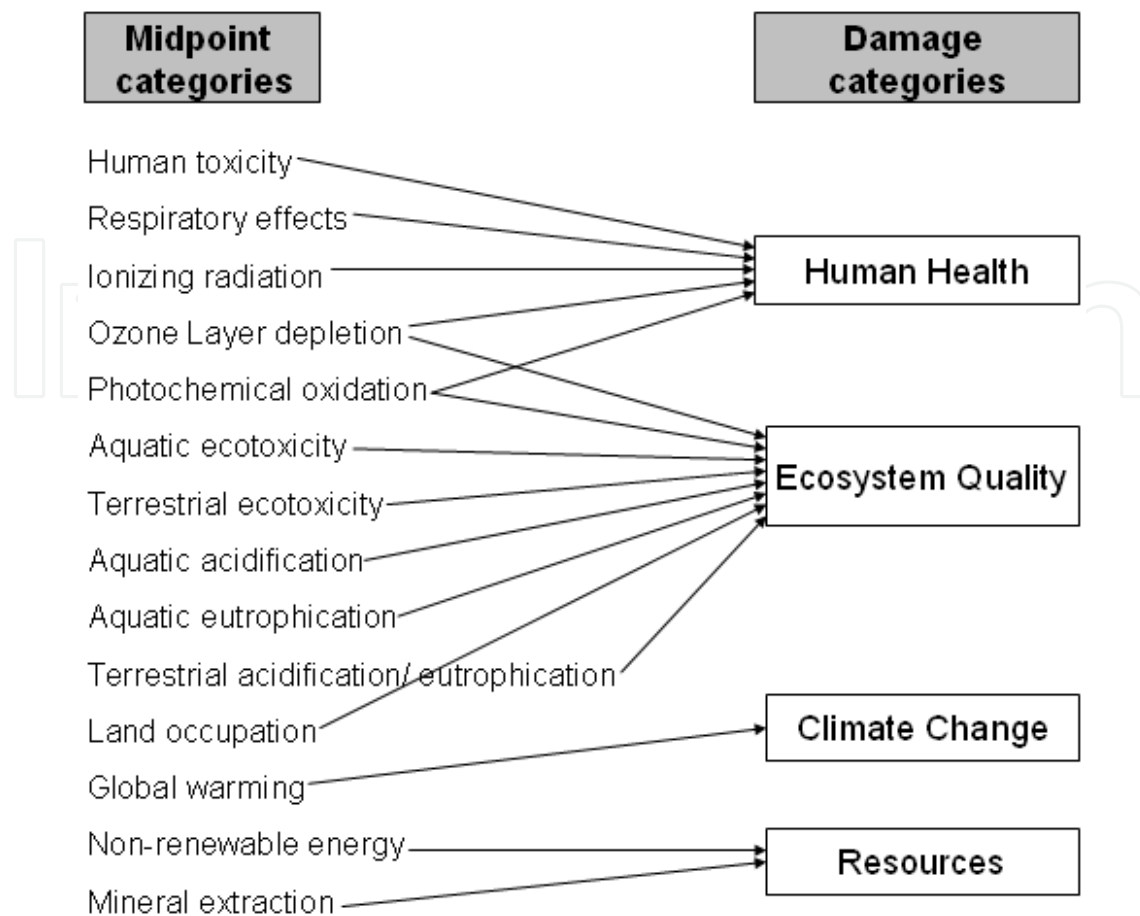
Another important aspect in selecting the right life cycle impact assessment method is the method's geographic coverage. Some methods were intended for specific countries only and they are applicable to their specific conditions, while other ones are more general [17]. In analyses of technology used in Europe, it is extremely important to consider methods which are suitable in conditions which prevail in Europe.

It is recommended to carry out LCA analyses using several methods of life cycle impact assessment; this enables verification of the results obtained by a given method and more objectivity. Such approach enables a sensitivity analysis as well as adjustment of any analytical error that may occur. Checking the analysis by doing it with another method. It is to remember that it is a methodological error to compare midpoint and endpoint methods.

The most popular methods within SimaPro include: Eco-Indicator 99 and Impact 2002+. Special emphasis in the two methods is put on substances which persists in the environment for many years, therefore, a long-term horizon is taken into account. Eco-Indicator is intended for damage assessment and is available in three variants: egalitarian (E), individual (I) and hierarchic (H). The egalitarian variant covers a very long-term horizon (even as long as 200 years), while the individual variant applies to a short one (of about 20 years). The hierarchic variant covers a balanced time horizon, while taking into account the long- and short-term perspectives. Therefore, impact assessment is frequently carried out according to the hierarchic method. Established in the method are three endpoints: human health, quality of the ecosystem, and depletion of resources. The following impact categories are deemed to be destructive to human health: climate changes, ozone depletion, carcinogens, destructive respiratory substances, and radiation. Damage to human health is expressed in DALY (Disability Adjusted Life Years) [18], the unit is used by WHO and the World Bank for health-related statistics. According to the method, the following impact categories are deemed to cause damage to the quality of the ecosystem: acidification, eutrophication, land use, and ecotoxicity. Generally, such damage is expressed as a diversity of species. In the acidification, eutrophication, and land use categories, the size of damage is expressed as the fraction of species which are exposed to extinction (*Potentially Disappeared Fraction* PDF) [3]. Damage which causes depletion of resources is expressed, in MJ, as an extra amount of energy which will be required in future for mining mineral and solid fuels.

The method Impact 2002+ combines the midpoint and endpoint approaches, allocating the results to fourteen categories which have an impact on four areas of damage (damage categories): human health, quality of the ecosystem, climate changes, and resources (Figure 2). In that method, climate changes are regarded as a separate final category.

CML2000 is an example of the midpoint method, limited only to impact categories, without using damage categories. It is based on the following impact categories: ozone depletion, human toxicity, three kinds of ecotoxicity (affecting inland waters, sea water, and soil), photochemical oxidation, global warming, acidification, eutrophication, and depletion of abiotic resources (minerals and fossil fuels). Land use is not taken into account in that method [20].



**Figure 2.** General diagram of the method Impact 2002+[19]

The methods referred to above are merely examples, showing the diversity and flexibility of software and methods for LCA analyses. The proper methodology always depends on the intended application, scope of analysis, the reasons for carrying out the study, as well as the intended audience [16].

## 5. Life cycle of engine fuels and biofuels

### 5.1. Steps of the life cycle of engine fuels and biofuels

Commonly used liquid fuels with biocomponents include the following [14]:

1. Fuels with the normative content of biocomponents:
  - a. gasoline with up to 5%(V/V) ethanol (PN-EN 228);
  - b. diesel fuel with up to 7%(V/V) of FAME (PN-EN 590);
  - c. 100%(V/V) FAME as a pure fuel (PN-EN 14214+A1).
2. Fuels with the non-normative content of biocomponents:

- a. gasoline with from 70 to 85%(V/V) of ethanol;
- b. diesel fuel with 20%(V/V) of FAME;

for use in vehicles having suitably adapted engines.

Essentially, five steps of life cycle exist both for the conventional fuels and biofuels: (Fig. 3):

1. Material acquisition (by mining or by cultivation of energy plants).
2. Transport.
3. Fuel production process.
4. Transport and distribution.
5. Use.

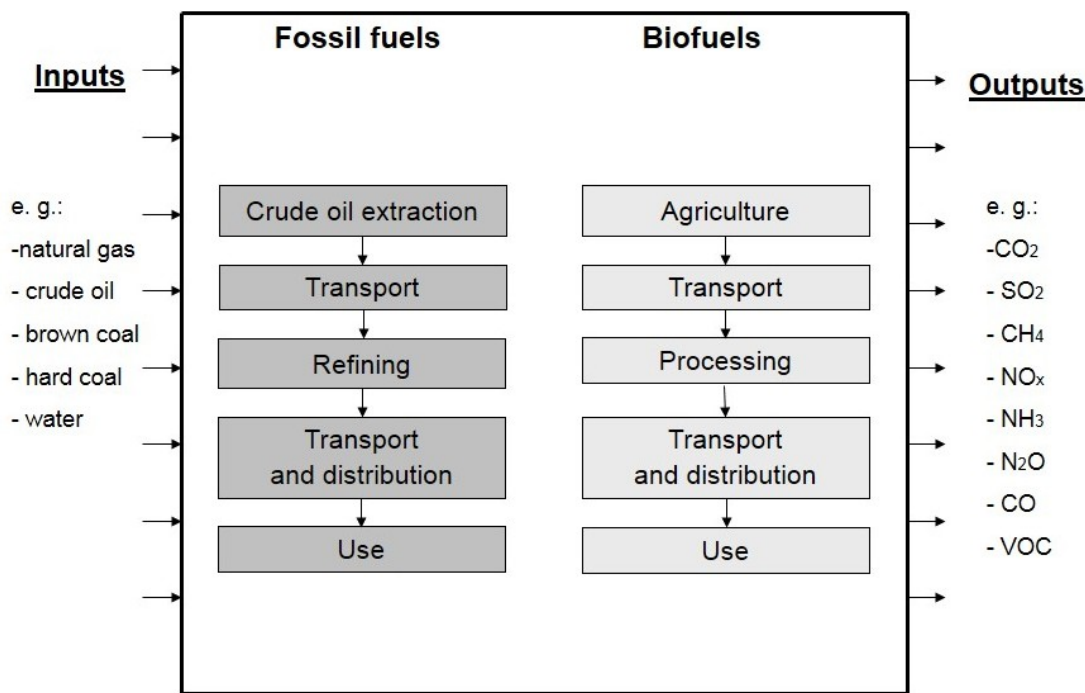


Figure 3. The process tree for petroleum-based fuels and biocomponents

Essential differences exist between the life cycle of fuels and biofuels at the steps of material acquisition and fuel production.

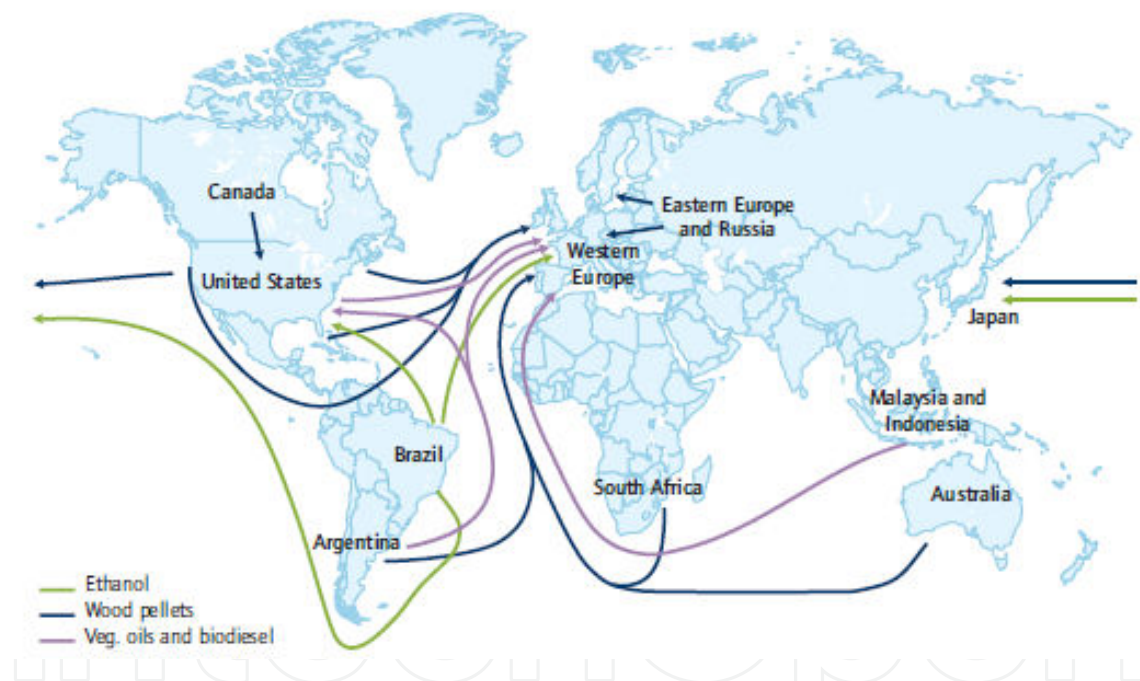
For the conventional fuels (gasoline, diesel fuel) the substrate they are made from is a fossil energy carrier in the form of crude oil, extracted from oil fields. Conventional extraction methods include drilling onshore or offshore wells; strip mining, in situ and other techniques are used, depending on the type of field or deposit.

By contrast, biofuels are typically made from biomass originating from dedicated plantations or from waste. 1<sup>st</sup> generation biodiesel is made from edible oil plants, such as soy, rape,



sunflower; bioethanol is made from such plants as sugar cane, sugar beets, rye, corn, potatoes etc. [22] Biomass plantations often require the use of fertilizers and plant protection agents, involve high emissions and energy consumption (especially production of mineral nitrogen fertilizers). Additional emissions at this step involve combustion of fuel (mainly diesel fuel) during the field works connected with starting a plantation, its maintenance, harvesting, and liquidation [13]. Both factors may have a considerable impact on the end results of LCA analysis.

Transport takes place between the essential processes of the life cycle of fuels and biofuels. The transport of crude oil to refineries is typically long-term and uses pipelines (land transport) and tankers (marine transport). Vegetable raw materials for the production of biofuels are usually transported locally although, owing to the availability and prices of raw materials or intermediates, their transport can also be international (long-distance) (Fig. 4). Such basic differences in the types of transport means and distances must obligatorily be taken into account in LCA analyses.



**Figure 4.** World biomass shipping today [21]

Important differences exist also between the processing of conventional fuels and biofuels.

Refinery processing is carried out by fractionation of raw material in the process of atmospheric distillation and vacuum distillation (for high-boiling components). In the subsequent steps, the fractions are converted (thermal cracking, catalytic cracking, hydrocracking), improved (catalytic reforming, isomerization, alkylation), refined (hydrotreating) and sent downstream to obtain specific compositions. For the purposes of LCA analyses, it is important to take into account allocations, because of the huge diversity of crude oil refining products.



For 1<sup>st</sup> generation bioethanol, the main steps of the production process include: preparation of raw material, mashing, fermentation, rectification, and dewatering (by azeotropic distillation, extraction distillation, or pervaporation), which is one of the most expensive and energy-consuming processes of the production of anhydrous ethanol intended for use as a fuel.

The production of 1<sup>st</sup> generation biodiesel involves the following steps: oil pressing or extraction (or the use of waste fats or oils), transesterification using methanol (or ethanol).

The two above-mentioned types of biofuels are the most popular ones globally and their manufacturing technologies are well known and understood. In the case of the consequent generations of biofuels, manufacturing technology is highly diversified, depending on the raw materials used, and these are highly various, including: non-edible biomass (energy plants, organic waste substances, or nonedible oilseeds). This group of raw materials comprises the following [22]:

- bioethanol, biobutanol and mixtures of higher alcohols, as well as their derivatives obtained by advanced hydrolysis and fermentation of lignocellulose based on biomass (other than raw materials for use as food);
- synthetic biofuels – obtained from biomass processing by gasification followed by a suitable synthesis technique to obtain liquid components for fuels in BtL (Biomass-to-Liquid) processes and those resulting from the processing of biodegradable industrial and municipal waste in WtL (Waste-to-Liquid) processes;
- fuels for spontaneous-ignition engines – obtained by the processing of lignocellulose from biomass in Fischer-Tropsch processes, including synthetic biodiesel based on a composition comprising lignocellulose products;
- biomethanol – obtained in processes involving the transformation of lignocellulose, including Fischer-Tropsch synthesis, also using waste carbon dioxide;
- biodimethylether (bio-DME) obtained by the thermochemical processing of biomass, such as bioethanol, biogas, syngas originating from biomass transformation;
- biodiesel as a biofuel or a component of fuels for spontaneous-ignition engines – obtained by refining with hydrogen (hydrogenation) of vegetable oils and animal fats;
- biodimethylfurane (bioDMF) – originating from the processing of sugars, including cellulose, in thermo- and biochemical processes;
- biogas – as a synthetically obtained natural gas-biomethane (SNG), obtained by gasification of lignocellulose, suitable synthesis, as well as by purification of biogas from agricultural sources, landfills, and effluents;
- biohydrogen – obtained by gasification of lignocellulose followed by the synthesis of gasification products, or in biochemical processes.

When carrying out a life cycle assessment for the production technology of the 2<sup>nd</sup> generation biofuels mentioned above, one should keep in mind that the technology may either be experimental (only bench or semi-technical scale) or it may be used in a limited number of

commercial plants. This affects the quality, level of uncertainty, and possibility of input data verification, which ought to be taken into account during interpretation of the results of such analysis.

## 5.2. The role of storage in the life cycle of engine fuels and biofuels

From the point of view of the market, storage has an important role in the operations and functioning of enterprises. Among other things, storage helps avoid the negative impact of fluctuations in production/consumption, disturbances in production and supplies. Storage of liquid fuels is necessary for the accumulation of strategic reserves to guarantee national energy security. The strategic reserves are expected to guarantee the functioning of economy for 90 days. Long-term storage is essential nowadays for being able to avoid temporary energy crisis situations, resulting from disturbances in crude oil and gas supplies.

Industrial practice of storage of fuels has developed into long-or short-term storage. Long-term storage is a storage at the limit of manufacturer's guarantee and is called a maximum permissible period of storage. Storage on an as-needed basis is called short-term storage. Liquid fuels with a content of biocomponents may be stored for a short term only [15]:

- gasoline with ethanol – 6 months max.;
- diesel fuel with esters – 3 months max.;
- FAME – 1 month max.

A life cycle assessment analysis of petroleum-based fuels enables locating those spots in the production chain of gasoline or diesel fuel which have the highest environmental impact. Besides, LCA helps find out the extent to which emissions are reduced by the use of biocomponents, by comparing the environmental impacts, caused in their entire life cycle. Moreover, it is possible to establish what kinds of environmental risks are caused by the acquisition of raw materials, their transport, production, and storage of transport fuels, compared with the environmental impact arising during the life cycle of petroleum-based fuels.

The life cycle of petroleum-based fuels or biofuels is extended to encompass the processes during which energy from nonrenewable sources is used and which generate emissions to all elements of the ecosystem in every step of their life cycle contemplated in the assessment.

A process tree for petroleum-based fuels and biocomponents is shown in Fig. 3 so as to illustrate the consequence of the storage of liquid fuels with biocomponents in the environmental aspect.

Storage is not included in the major process group. Each of the essential processes of the life cycle of petroleum-based and biofuels shown above comprises intermediate processes as well as auxiliary and side processes etc. Storage processes take place in every step of the life cycle of liquid fuels:

- storage of pre-refined crude oil (*Crude oil extraction*) (Fig. 5);
- storage of crude oil during transport by sea in tankers (*Transport*) (Fig. 6);

- storage before processing – crude oil (*Refining*) (Fig. 7);
- storage after processing – basic liquid fuels (*Refining*) (Fig. 7);
- storage after blending of base fuels with improvers (*Refining, Distribution*) (Fig. 7);
- storage after blending of base fuels with biocomponents (*Refining, Distribution*) (Fig. 8).

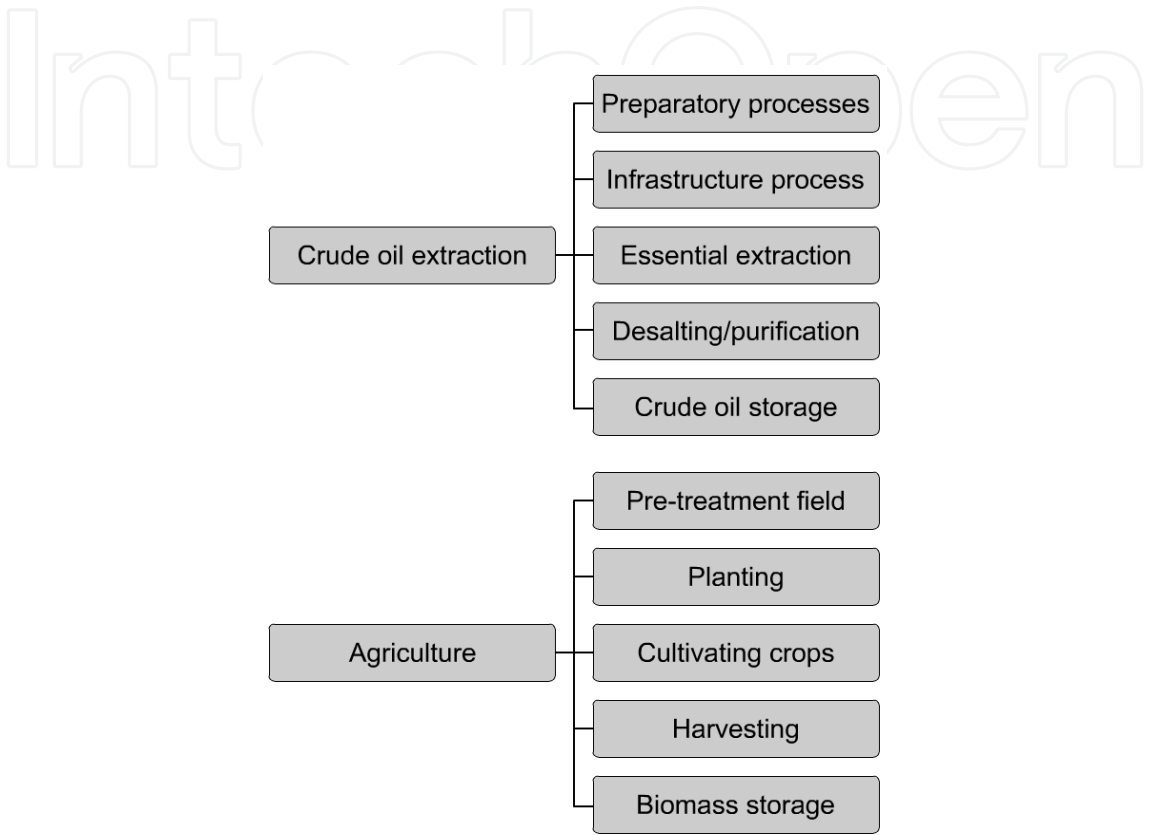


Figure 5. Storage in pre-refining of crude oil and biomass

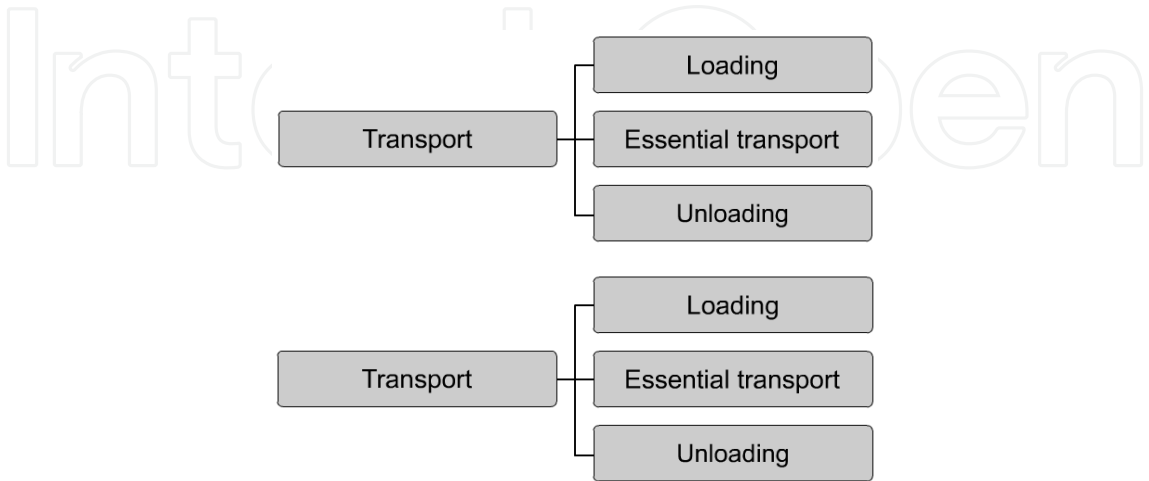
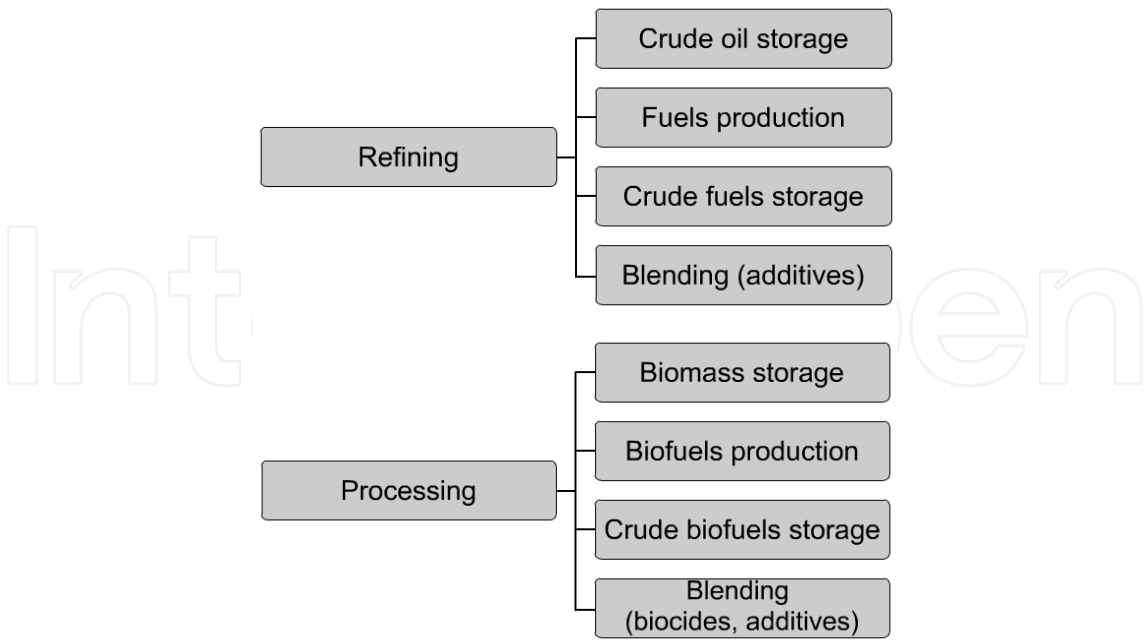
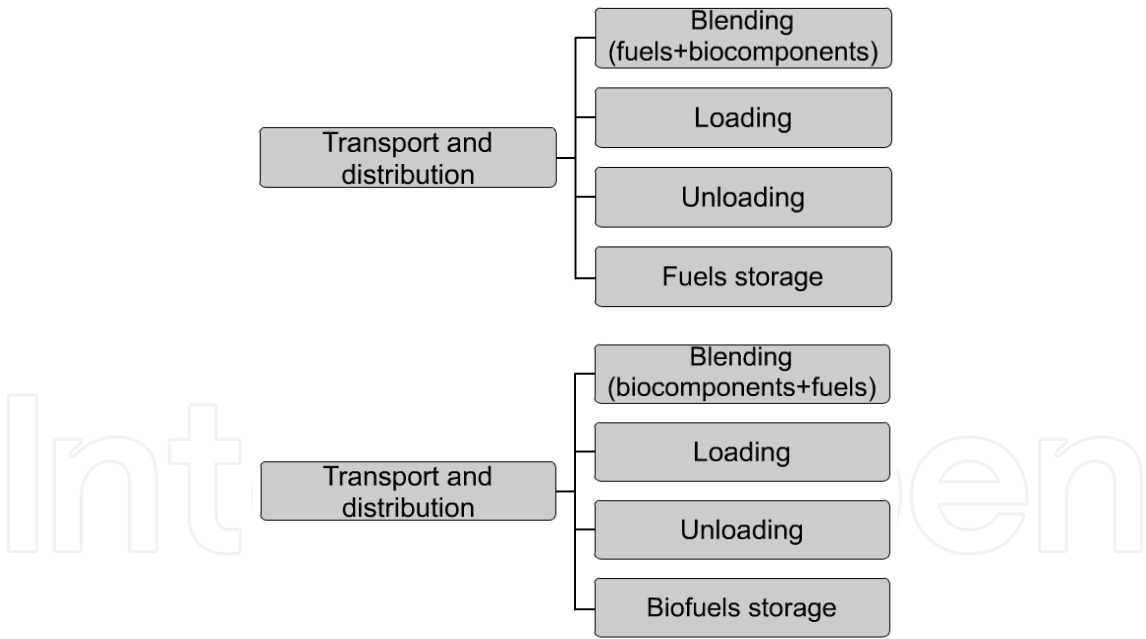


Figure 6. Storage in transport of crude oil and biomass



**Figure 7.** Storage in processing of crude oil/petroleum-based fuels and biomass/biofuels



**Figure 8.** Storage in transport of petroleum-based fuels and biofuels

The importance of storage processes in the context of environmental protection depends on the potential pollution and on the physico-chemical properties of the products stored. Differences exist and should be noted, between hazard (natural chemical properties) and risk (probability that hazardous properties exist and will be released from stored products, causing damage to humans and the environment). Various products or substances create various risks

due to their properties, such as low flash point, flammability, toxic effect on human health and on the environment.

In storage facilities, two operating conditions are identified in which emissions may be released when carrying out operations: normal operating conditions (including the handling of products to/from storage facility, and cleaning) and accidents or major failures.

Such emissions may occur in the following forms:

1. Emissions to the air – in normal operating conditions, significant emissions into the air in connection with storage of liquid fuels in industrial practice include the following groups:
  - those which occur in the process of filling/emptying the tanks;
  - those which occur during the tank breathing process, i.e., emissions caused by temperature increase due to vapor expansion, which is followed by emission;
  - temporary emissions from collar gaskets, connections and pumps;
  - those which occur during sampling procedures;
  - those which occur in effect of cleaning operations.
2. Discharge to water (direct/indirect via waste water system and treatment plants) – in normal operating conditions, significant emissions into water in connection with the storage of liquid fuels in industrial practice include the following groups:
  - effluent from chemical storage, tanks, leakage water, etc.
  - discharge from the waste water system;
  - washing effluents;
  - cleaning effluents.
3. Noise – in storage facilities essentially only in reloading processes:
  - emissions from pumping plants;
  - traffic of vehicles (receiver tanks) and vent valves.
4. Waste in the following forms:
  - residues or products below standard quality;
  - waste material from the vent cleaning systems;
  - spent containers;
  - deposits;
  - cleaning agents, where applicable.

Other than in normal operating conditions, emissions occur as a result of accidents and major failures of equipment. Emissions caused by accidents and failures typically take place over a

short period of time and are much more intense than those taking place in normal operating conditions.

Storage processes also comprise transport and handling systems. Liquid fuels are transported by means of pipelines which are connected to the storage tank, but also by means of flexible hoses or marine loading arms to be attached to tanker trucks, railway tankers or tank ships. A liquid fuel handling system includes the fuel transfer by means of pipes to/from storage tanks, for instance, using pumps.

In the research practice, analyses assessing environmental aspects cover five major processes. Storage of fuels, even though it has an important role in the market, is not taken into account in LCA as a major process. Because of its low energy consumption and emission levels (emissions occur mainly by fuel evaporation from the storage tanks in the process of storage and tanker filling), storage is a mid-way process of low importance. Therefore, in most life cycle analyses, storage processes are either excluded from assessment or their accompanying emissions are included in the major processes.

## 6. Conclusion

A growing social awareness and more stringent legal requirements in environmental protection issues lead to arousing interest in activities and technologies with a potential to reduce the adverse environmental impact of man. In selecting the most suitable ones, it is convenient to use LCA – a comprehensive life cycle analysis, enabling the full assessment of the environmental impact of the entire manufacturing process, starting from the acquisition of raw materials and ending with the final step of disposal of waste arising in the process of product use. LCA offers numerous environmental and economic benefits. The method is potentially helpful in making investment decisions, enabling reduction of the consumption of materials and energy, as well as disposal of any byproducts and waste that arise.

Discussed in this chapter is the methodology for life cycle assessment (LCA), as a method enabling an assessment of the environmental impact of the production of engine fuels and biofuels, especially the storage process. A comparison between the LCA technique vs. WtW analysis, and of various types of computer software is made in the aspect of the capabilities and justification for their use in assessing the environmental impact of the manufacturing and use of fuels and biofuels. The respective steps of LCA and the requirements and rules of assessment are discussed, taking into account their impact on the final LCA result. Which specific method or software is selected depends on the goal and scope of analysis, end user, and the available input data. Moreover, it is necessary to take into account the various environmental impact categories which are specific for the given product system.

There are a number of tools in the market which facilitate the assessment of the environmental impact of products, although it is up to the user to choose the suitable tool for a particular problem. The most popular and most frequently selected tools include SimaPro (Dutch) and Gabi (German). Moreover, the most useful tool, dedicated to the calculation of greenhouse gas



emissions accompanying the production of biofuels which are available in Europe now, is BIOGRACE – a calculator based on the methodology for assessing greenhouse gas emissions caused by the production and use of transport fuels, biofuels, and biofluids, referred to in the Directive 2009/28/EC, thereby facilitating the implementation of those provisions of the Directive, concerning sustainable production of biofuels.

Essentially, five steps of life cycle exist both for conventional fuels and biofuels: material acquisition, transport, fuel production process, transport and distribution, and use. Despite its important function in the market, storage is not taken into account in LCA as a major process because of its low energy consumption and emission levels. Therefore, emissions accompanying storage processes are contemplated as part of the major processes or are excluded from analysis in most life cycle analyses.

## Author details

Izabela Samson-Bręk<sup>1</sup>, Barbara Smerkowska<sup>1</sup> and Aleksandra Filip<sup>2</sup>

<sup>1</sup> Automotive Industry Institute, Renewable Energy Department, Poland

<sup>2</sup> Automotive Industry Institute, Fuels, Biofuels and Lubricants Department, Poland

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