APPLICATION OF THE LIFE CYCLE ASSESSMENT (LCA) METHOD TO THE ESTIMATION OF ENVIRONMENTAL IMPACT OF THE GENERATION OF BIOGAS AS AN ENGINE FUEL

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Summary

The "Life Cycle Assessment" (LCA) "is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment, and to assess the impact of those energy and materials used and releases to the environment. The assessment includes the entire life cycle of the product, process or activity, encompassing: extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal. The LCA orients the assessment of environmental impact of a product system to the areas of ecosystem, human health, and resources used." In the light of the obligations imposed by the European Union on its member states regarding the minimisation of environmental impact of the fuel industry, the LCA method helps to meet these requirements and is a useful tool to fulfil such obligations. It covers the whole life cycle of a fuel, from the raw material extraction, through the fuel production and use, to the procedures of management of the fuels that do not meet the applicable standard requirements.The life cycle assessment (LCA) method has been described as one of the methods that make it possible to estimate the environmental impact of the process of manufacturing biogas as a fuel intended for internal combustion (IC) engines. Individual stages of the LCA process as well as the assessment preparation principles and requirements are governed by the ISO 14000 series of standards (from 14040 to 14049) and the corresponding Polish equivalents.

Keywords: biogas, LCA, life cycle assessment, fuel, ISO, input data, output data

1. Introduction

The "Life Cycle Assessment" (LCA) is a relatively new technique of environmental management. It makes it possible to identify the most important environmental aspects and to assess their environmental impacts at all the stages of a product life ("from-cradle-to-grave," i.e. from raw material extraction through production process, product use, and waste disposal or recycling).

In the light of the obligations imposed by the European Union on its member states regarding the minimisation of environmental impact of the fuel industry, the LCA method helps to meet these requirements and is a useful tool to fulfil such obligations. It covers the whole life cycle of a fuel, from the raw material extraction, through the fuel production and use, to the procedures of management of the fuels that do not meet the applicable standard requirements.

The application of the LCA method to the fuel sector makes it possible to identify and, to become aware of, the interrelations between human activities and their impacts on the environment. This also provides an important source of information in the process of taking decisions aimed at minimisation of the harmful impact of fuel production on the environment and, in consequence, at environmental improvement.

An analysis of the possibilities of using the life cycle assessment to estimate the environmental impact of biogas as an engine fuel has been presented in this paper.

2. Historical background in brief

The first mentions related to LCA could be found in Harold Smith's reports presented at the World Energy Conference in 1969. The Smith's studies concerned the generation of various energy types by means of selected chemical processes. One of the first companies that took an interest in the making use of these analyses in practice was Coca-Cola, which commissioned evaluation of beverage containers. The theoretical basis for the LCA methods was defined at a conference in Vermont in 1990. Due to increasing interest in the LCA approach, the Society of Environmental Toxicology and Chemistry (SETAC) and the International Organisation for Standardisation (ISO) commenced work on the unification and standardisation of the LCA methods. This work resulted in the preparation of a number of standards and, in particular, the formulation of a definition, according to which "*LCA is a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment, and to assess the impact of those energy and materials used and releases to the environment. The assessment includes the entire life cycle of the product, process or activity, encompassing: extracting and processing raw materials; manufacturing, transportation and distribution; use, re-use, maintenance; recycling, and final disposal. The LCA orients the assessment of environmental impact of a product system to the areas of ecosystem, human health, and resources used.*"

3. Description of the LCA process

The life cycle assessment (LCA) is governed by the ISO 14000 series of standards (from 14040 to 14049) and the corresponding Polish equivalents (Table 1). These standards provide requirements and guidelines for the preparation of evaluation reports as well as principles of interpretation of evaluation results and templates of the documents required.

Table 1. The ISO standards concerning the life cycle assessment.

ISO standard	Equivalent Polish standard
ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework	**PN-EN ISO 14040:2009** Zarządzanie środowiskowe – Ocena cyklu życia – Zasady i struktura
ISO 14044:2006 Environmental management – Life cycle assessment – Requirements and guidelines	**PN-EN ISO 14044:2009** Zarządzanie środowiskowe – Ocena cyklu życia – Wymagania i wytyczne
ISO/TR 14047:2003 Environmental management – Life cycle impact assessment – Examples of application of ISO 14042	**PKN-ISO/TR 14047:2006** Zarządzanie środowiskowe – Ocena wpływu cyklu życia – Przykłady stosowania ISO 14042
ISO/TS 14048:2002 Environmental management – Life cycle assessment – Data documentation format	**Polish version of the specification** Zarządzanie środowiskowe – Ocena cyklu życia – Format dokumentowania danych
ISO/TR 14049:2000 Environmental management – Life cycle assessment - Examples of application of ISO 14041 to goal and scope definition and inventory analysis	**Polish version of the report** Zarządzanie środowiskowe – Ocena cyklu Życia – Przykłady stosowania ISO 14041 do określania celu i zakresu oraz analizy zbioru
ISO 14050:2009 Environmental management – Vocabulary	**No Polish equivalent available**

The product evaluation for life cycle assessment purposes may be carried out for the same specific products with various degrees of minuteness, depending on the needs of the prospective users of evaluation results and the availability of input data. In these terms, the LCA studies may be classified in three basic categories:

- *Screening LCA:* In most cases, this option is adopted within the scope of a single system or when short time of the analysis or low budget are particularly important. For the analysis, secondary estimates obtained from existing databases or statistical reports are used as the input data. In this option, the carrying out of a sensitivity analysis is recommended so that the actual influence of the results obtained on the essential issues of the analysis is checked. Time needed: From a few days to about one month.
- *Simplified LCA:* Used at decision-taking processes related to product development and communication strategies. The input data used may be sourced from existing databases but they should be supplemented with current literature data and primary data coming

from product suppliers, makers, or other links of the product life chain, i.e. directly from inquiries or measurements. A sensitivity analysis must be carried out to verify the important assumptions. Time needed: From a few weeks to several months.

- *Detailed LCA:* Used for full-scope LCA product examination and for comparative evaluation of various products. In this case, detailed primary data directly obtained from measurements, analyses, and inquiries as well as current literature data and statistical data of verified quality are used as the input data. Pursuant to provisions of the ISO 14040 standard series, an independent reviewer should participate in each phase of the LCA process. Descriptions of all the procedures adopted, reasons for the choices made and for any incompleteness of the input data, as well as a comprehensive sensitivity analysis are required. Time needed: From a few months to one year.

According to the ISO standards concerning LCA, the LCA process consists of four phases as presented in Fig. 1:
- Goal and Scope Definition;
- Life Cycle Inventory (LCI);
- Life Cycle Impact Assessment (LCIA);
- Life Cycle Interpretation.

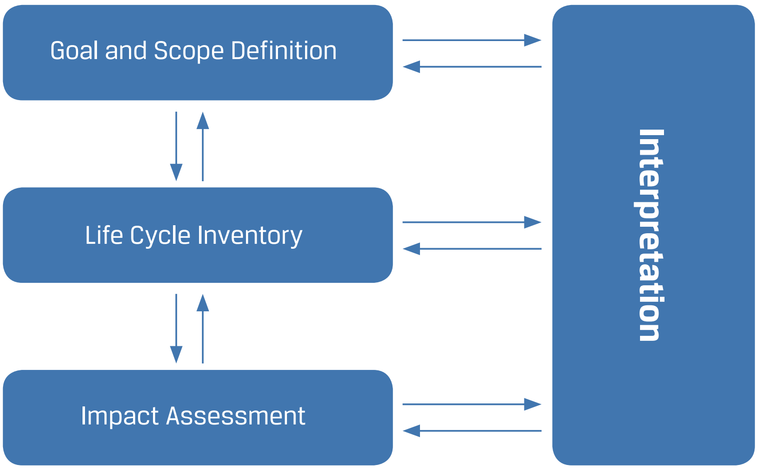

Fig. 1. LCA phases.

Source: Author's study, based on Polish Standard PN-EN ISO 14040:2006.

3.1. Goal and scope of the analysis

This is the first phase of the LCA process, during which decisions determining the whole analysis are taken. The Polish Standard PN-EN ISO 14040:2006 regulates the notion of goal of evaluation, which should unequivocally define the intended application, reasons for undertaking the evaluation, and prospective user of the evaluation report. The goal of this evaluation is to determine the environmental impact of the making and use of biogas as an engine fuel. The scope of the evaluation directly stems from the goal assumed and covers the energy production process.

According to Polish Standard PN-EN ISO 14041:2006, the formulation of the scope of evaluation should include the following information:

- Function of the product system;
- Functional unit;
- Boundaries of the product system;
- Impact types, methods of impact assessment, and interpretation of assessment results;
- Data quality requirements;
- Assumptions;
- Exclusions.

The "functional unit" is a "measure of the effects produced by functional outputs of a product system." For the life cycle assessment of biogas, the functional unit has been defined as the quantity of fuel necessary for covering a distance of 100 km in urban conditions. The reference flow should be defined here as the quantity of petrol necessary to cover the same distance in the same conditions.

The system boundaries make it possible to define the unit processes that should be covered by the analysis. The defining of system boundaries is influenced by many factors, such as goal of the analysis, assumptions made, and exclusions adopted. According to the goal of this evaluation, the boundaries of the system under analysis encompass transport of raw material, biogas generation in a fermentation tank, purification of the gas generated, and use of the gas (Fig. 2). The system also includes the transportation of fermentation sludge to the field where the sludge is applied as a fertiliser; however, the fertiliser (sludge) application costs are outside of the system boundaries. The system boundaries do not encompass, either, the production of raw material handling trucks or components of process installations.

The substrate used in the methane fermentation process and consisting of animal excrements is simultaneously a waste material generated in result of cattle, pig, and poultry breeding; therefore, the acquisition of this material is also outside of the system boundaries.

The biogas production process wastes, except the fermentation sludge, chiefly consist of substances emitted to the atmosphere or water during the biogas purification process.

For biogas treatment, water scrubbers have been recognised as the best solution from economic and environmental protection point of view. This is the most popular biogas treatment technology and the necessary installations are widely available in the market. In the scrubber column, carbon dioxide is dissolved in water and the concentration of gaseous methane increases. Thus, the methane content of biogas at the scrubber outlet is significantly raised. The water leaving the absorption column flows to a storage tank. The waste gas containing some recoverable methane quantities is returned to the raw gas inlet. If the water is to be subjected to a recycling process then it is directed to a desorption column filled with plastic packing. Before the water is recycled and returned to the absorption column, it is cooled to a temperature at which a significant difference between the solubility of carbon dioxide and methane may be achieved.

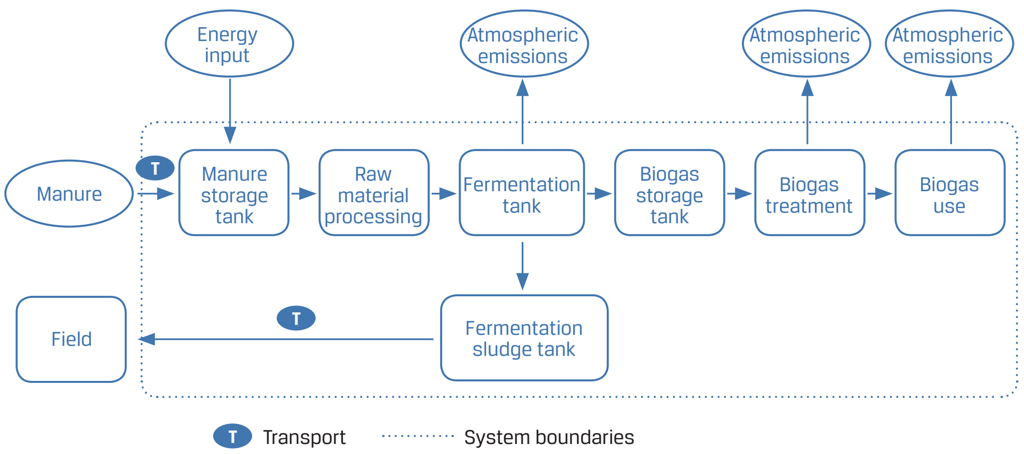

Fig. 2. Schematic diagram of the LCI model of the production chain under evaluation, showing all the stages taken into account in the analysis.

Source: Author's study.

The geographic scope of the analysis ranges from local to national. Some of the data are specific for the locality (e.g. raw material acquisition), while others are of the national type. Table 2 shows the time, geographic, and technological scope of the analyses carried out for the main product as well as the width and depth of the system.

Table 2. The time, geographic, and technological scope of the analyses carried out as well as the width and depth of the system.

Product	Production and use of biogas as an engine fuel
System width	Cradle-to-grave
System depth	Up to the 2nd level
Time scope of the product system	15 years
Time scope of the data	Up to 5 years
Geographic scope	Local to national
Technological scope	Modern technologies

3.2. Life cycle inventory

At the second stage of the life cycle analysis, the data related to inputs from, and outputs to, the environment are gathered and analysed (which is generally referred to as "life cycle inventory" or LCI). According to Polish Standard PN-EN ISO 14040:2006, the data for individual unit processes that take place within the product system boundaries may be classified in the following types:

- Input data: energy input, raw material input, auxiliary data, and others;
- Output data: products, intermediate products, and wastes;
- Releases to air, water, and land; and
- Other environmental aspects.

In the LCI, the input data, i.e. those concerning materials and energy, and the output data, i.e. those concerning the main products and by-products, wastes, and environmental releases (see Table 3) are gathered in the form of inventory tables where the consumption of natural raw materials and intermediate products and the output of wastes generated are presented in quantitative form. An important part of the data gathering process is the verification of completeness and quality of the data acquired.

Pursuant to provisions of Polish Standard PN-EN ISO 14044:2006, the data selection process should be carried out with maximum care and diligence. The most valuable and desirable data are those obtained from analyst's own research work. If such data are unavailable, data found in literature or in the existing databases may be allowed, according to the Standard.

Table 3. Input and output data for the process of generation of biogas of 98% methane content.

Input data "from nature"	
Water	For the gas treatment process
Input data "from technosphere" (materials, fuels, electricity, and heat)	
Main substrate	Liquid manure
Fuel consumption	Consumption of fuels at raw material handling
Electricity consumption	Consumption of electricity by process installations (at biogas generation and treatment processes)
Heat consumption	Consumption of heat used to maintain appropriate temperature in the fermentation tank
Output data	
Main product	Biogas of 98% methane content
Wastes and environmental releases	
Solid waste	Fermentation sludge, used as a fertiliser (avoided production of ammonium nitrate and nitrogenious fertilisers)
Releases to air (atmospheric emissions)	CH_4
	CO_2
	NO_x
Releases to water	Wastewater generated at the biogas generation process

4. Life Cycle Impact Assessment

The goal of the life cycle impact assessment (LCIA) stage is to determine the environmental interrelations between all the inputs and outputs covered by the LCA scope and to estimate their environmental impact in quantitative terms.

At this stage, the LCI results are classified in appropriate impact categories, based on the environmental priorities adopted, with the local and regional constraints being taken into account. The impact categories are given specific weights depending on the degree of environmental impact of a given environmental factor. The LCIA consists of two groups of elements (PN-EN ISO 14044:2006):

- Obligatory, which include:
  - Selection of impact categories, category indicators, and characterisation models;
  - Assignment of LCI results to specific impact categories (classification);
  - Calculation of category indicator values (characterisation);
- Optional, which include:
  - Normalisation;
  - Grouping;
  - Weighting;
  - Analysing of data quality.

When impact categories are selected, the goal and scope of the analysis should be considered. Some analysis methods make it possible to present the results in the form of a single point represented by a numerical value; for others, the results are presented in the form of indicators separately characterised for each category. Pursuant to standards of the ISO 14040 series, however, the presentation of results in the form of a single value should be avoided and the use of methods providing a broader spectrum of possibilities to carry out the analysis is suggested. One of such methods is that named Eco-Indicator 99. In this method, 11 impact categories are distinguished:

- Carcinogens;
- Respiratory organics;
- Respiratory inorganics;
- Climate change;
- Radiation;
- Ozone layer depletion;
- Ecotoxicity;
- Acidification/eutrophication;
- Minerals;
- Fossil fuels;
- Land use.

At the life cycle assessment of the generation and use of biogas as an engine fuel, the category related to the impact on climate changes will be of the greatest importance (Table 4). The significance of the above categories is chiefly related to the emission of greenhouse gases and other harmful substances during both biogas generation and combustion of the biogas in an engine.

The factors that have the highest impact on the climate change category are the methane loss during the transport of raw material to process installations and during the biogas generation process (about 3% in total) as well as the carbon dioxide generated during biomethane combustion. Methane is one of the "greenhouse gases," which cause climate changes generally named "greenhouse effect." The influence of methane on enhancement of the greenhouse effect is estimated as being 21 times as high as that of carbon dioxide, according to various experts' opinions.

Table 4. LCIA impact categories.

Impact category	LCI data	Indicator
Climate change	Carbon dioxide (CO_2) Nitrogen dioxide (NO_2) Methane (CH_4)	Conversion of LCI data into carbon dioxide (CO_2) equivalent
Acidification	Sulphur oxides (SO_x) Nitrogen oxides (NO_x) Hydrochloric acid (HCl) Ammonia (NH_3)	Conversion of LCI data into hydrogen ion (H^+) equivalent
Eutrophication	Phosphates (PO_4) Nitrogen monoxide (NO) Nitrogen dioxide (NO_2) Nitrates Ammonia (NH_3)	Conversion of LCI data into phosphate (PO_4) equivalent

For other impact categories, such as acidification or eutrophication, the environmental impact of biogas is compensated to a significant extent by the use of fermentation sludge as a fertiliser and, in consequence, by avoiding the production of ammonium nitrate and other nitrogenous fertilisers. The production of mineral fertilisers requires high energy input derived from fossil fuels and the use of such fertilisers causes significant release of nitrogen compounds and thus enhances the acidification and eutrophication processes and the ozone layer depletion.

5. Interpretation of the LCA results

The interpretation is the last phase of the LCA process; it accompanies all the process stages discussed above, from the goal and scope definition right to the life cycle interpretation. The basic objective of the interpretation phase is to review and examine the results and to check their completeness, coherence, and usability from the point of view of the assumed goals and scope of the analysis. The last phase of the LCA process helps to formulate final conclusions, to clarify the constraints, and to formulate guidelines aimed at a reduction of environmental impacts.

The LCA is an iteration technique; therefore, the interpretation of the analysis results obtained at the current life cycle assessment stage may have an influence on changing the analysis conditions originally assumed. The results are presented in the form of a report. Based on the information provided in the report, decisions are taken to minimise the harmful impact of the activities conducted and to choose the best engineering solutions aimed at improvement of the environmental quality of the product.

6. Conclusions

The fuel industry is one of the greatest emitters of greenhouse gases and other substances that are environmentally harmful. It has a huge environmental impact. A chance to reduce this negative impact is the searching for new energy carriers that would be more environmentally sound than fossil fuels. The agricultural biogas used as an engine fuel becomes now an energy carrier of this kind.

The rising level of social consciousness and increasingly stringent environmental protection requirements result in growing interest in the technologies that might reduce negative environmental impacts. A useful aid in the selection and modification of the technologies is the life cycle assessment (LCA) method; thanks to its comprehensive nature, it enables full-scope assessment of the environmental impact of the entire production process starting from raw material acquisition, right to the final management of the wastes generated in result of the product use. When analysing the generation of agricultural biogas used as an engine fuel, a decision was taken that the LCA should cover the biogas generation, purification, and use as an engine fuel. An assumption was also made that the fermentation sludge being process waste may be utilised as a fertiliser for agricultural purposes.

The application of the LCA method brings numerous advantages, which include not only environmental but also economic benefits. This method may prove to be useful for the taking of investment decisions aimed at minimising the environmental impact of a process system. The LCA results may provide good grounds for the development of technologies that would satisfy all environmental protection requirements.

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