Eco-efficiency analysis methodology on the example of the chosen polyolefins production

K. Czaplicka-Kolarz, D. Burchart-Korol*, P. Krawczyk
Central Mining Institute, Plac Gwarków 1, 40-019 Katowice, Poland
* Corresponding author: E-mail address: dburchart@gig.eu

Industrial management and organisation

ABSTRACT

Purpose: This paper presents the eco-efficiency methodology and application of eco-efficiency analysis for the chosen polyolefins production. The article presents also main tools of eco-efficiency analysis: Life Cycle Assessment (LCA) and Net Present Value (NPV).

Design/methodology/approach: On the basis of LCA and NPV of high density polyethylene (HDPE) and low density polyethylene (LDPE) production, eco-efficiency analysis is conducted.

Findings: In this article environmental and economic performance of the chosen polyolefins production was presented. The basis phases of eco-efficiency methodology also presented.

Research limitations/implications: Eco-efficiency analysis allows economic and environmental assessment of products or/and technology. Taking into account economic and environmental aspects enables designing and the production of the most eco-efficiency product.

Practical implications: Eco-efficiency analysis allows economic and environmental assessment of products or/and technology. Taking into account economic and environmental aspects enables designing and the production of the most eco-efficiency product.

Originality/value: The paper presents eco-efficiency analysis as a new approach to products assessment. The eco-efficiency possibility is valuable for designers and manufacturers to design the most eco-efficiency product or technology.

Keywords: Eco-efficiency analysis methodology; Life Cycle Assessment (LCA); Net Present Value (NPV); high density polyethylene (HDPE); Low density polyethylene (LDPE)

1. Introduction

Eco-efficiency analysis allows integrated of economic and environmental assessment of products or technology. In this article methodology of eco-efficiency analysis is shown in case study of chosen polyolefins production.

This research focused on identifying and quantifying the environmental and economic impact of high density polyethylene (HDPE) and low density polyethylene (LDPE) production by using Life Cycle Assessment (LCA) and Net Present Value (NPV) integrated approach. The scope of the study included HDPE and LDPE production which associates with all emission

(air, water and soil), energy and materials acquisition. The results were then compared in order to identify the major environmental impacts during HDPE and LDPE production based on "gate-to-gate" approach. In this research, environmental impact categories were quantified using SimaPro 7.1 software with Eco-indicator 99 and CML 2 baseline 2000 V2.03 methods. Economic value was analysis by NPV. The functional unit was set to be 1000 kg of products.

2. Eco-efficiency conception

2.1. Definition of eco-efficiency

Eco-efficiency is a new concept in environmental management which integrates environmental considerations with economic analysis to improve products and technologies. Eco-efficiency is a strategic tool and it is one of the key factors of it sustainable development. Eco-efficiency analysis allows to find the most effective solution taking into account economic aspects and environmental compatibility of products/technologies.

The environmental impact should be as low as possible while the economic performance should be as high as possible [1]. The basic eco-efficiency tools are Life Cycle Assessment and Net Present Value.

The main purposes of eco-efficiency analysis are: reducing consumption of resources, reducing the environmental impact, increasing the value of added product and increase economic efficiency of production while reducing environmental impact.

The term eco-efficiency was proposed in 1990 by two Swiss researchers, Schaltegger and Sturm [2]. The term, eco-efficiency, was formally defined and adopted by the World Business Council for Sustainable Development (WBCSD) in 1991 as the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle, to a level at least in line with the earth's carrying capacity [3,4]. The WBCSD identified seven elements of eco-efficiency. They are:
1. Reduce material intensity,
2. Reduce energy intensity,
3. Reduce dispersion of toxic substances,
4. Enhance recyclability,
5. Maximise use of renewable resources,
6. Extend product durability,
7. Increase service intensity.

These elements or characteristics provide a guide to help businesses become more eco-efficient. Eco-efficiency is an instrument for sustainability analysis, indicating an empirical relation in economic activities between environmental cost or value and environmental impact [3].

The purpose of eco-efficiency is to maximise value creation while having minimised the use of resources and emissions of pollutants. Measuring ecoefficiency is important in order to measure the decoupling of economic growth and environmental pressure [5].

In the literature sources [3-8] can be find some formulas for eco-efficiency calculation based on the various available data on the environmental impact and the size and cost of production.

The eco-efficiency is calculated using absolute values for the product value and environmental influence. The two most important applications for eco-efficiency are as an internal tool for measuring progress, and for internal and external communication of economic and environmental performance [3]. The eco-efficiency analysis is used for comparing similar products in order to choose the best solution with the lowest cost and the least environmental impact (eco-effective solutions).

Central Mining Institute also has experience in eco-efficiency analysis and leads eco-efficiency analysis for the various materials, environmental and energy technologies for several years. The research methodology is based on eco-efficiency tool of environmental management and economic tools. Environmental assessment is based on LCA analysis, while economic indicators are calculated on the basis of NPV (Net Present Value) and LCC (Life Cycle Costing) [7,8].

2.2. Environmental assessment - Life Cycle Assessment

Life Cycle Assessment (LCA) is an environmental assessment method for evaluation of impacts that a product, process or technology has on the environment over the entire period of its life – from the extraction of the raw material through the manufacturing, packaging and marketing processes, the use, re-use and maintenance of the product or technology, to its eventual recycling or disposal as waste at the end of its useful life. LCA is a method of the evaluation of environmental aspects and potential impacts associated with all stages of the life of product, process and technology. The LCA method consists of four phases (according to EN ISO 14040:2006) [9,20]:
1. Goal and scope definition,
2. Inventory analysis LCI (Life Cycle Inventory),
3. Impact assessment LCIA (Life Cycle Impact Assessment),
4. Interpretation.

LCI (Life Cycle Inventory) is phase of Life Cycle Assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle. LCI studies comprise three phases: the goal and scope definition, inventory analysis and interpretation. LCIA (Life Cycle Impact Assessment) is phase of Life Cycle Assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impact for a product system throughout the life cycle of product or technology [9].

2.3. Economic assessment

Another key element of the eco-efficiency analysis is to assess the economic efficiency technologies. There are many methods of economic accounting, however, economic analysis for the purposes of calculating the eco-efficiency is carried out mostly on the basis of the absolute discount method of assessing the profitability and cost analysis of life cycle. Methods are applied to the net present value NPV and LCC (Life Cycle Costing) analysis. NPV method involves discounting the stream of revenue and expenditure and calculate their present value. It allows to

achieve comparability of receipts and payments at various times by converting them into value at the specified time base. Calculate the net present value NPV involves summing all the net benefits (net cash flows) associated with the technology / product performance throughout the economic life cycle which is discounted before aggregation, which boils down to one moment of time in order to unify their monetary value [10].

However, the LCC method is to identify and estimate all costs associated with the life cycle of a product or process, which relate directly to one or more decision makers in the life cycle (supplier, producer, user / consumer, business disposal), taking into account external costs, which may affect on decisions taken in the future [11].

NPV method in use to calculate the eco-efficiency has some drawbacks:

- The calculations take into account the benefits. They are mainly of revenue from product sales. Their level does not depend on the price of the product. Here the rule: the price should be such that the market has accepted it, but not lower. Production costs do not necessarily have any bearing on determining the price, it is important that the customer is willing to pay - what is the demand. This makes the calculation results less comparable between different technologies or products. In addition, the results obtained are dependent on market conditions.
- Depending on available data, the present scale of the project. The results obtained (NPV) are dependent on the size of the analyzed investment. In this situation, it is possible to compare only the technology of the same or very similar output.

In this section it is necessary to present in details assumptions and course of own researches to such an extent that a reader could repeat those works if he was going to confirm achieved results. In short papers those information should be given in as short a version as possible.

3. Characteristic of HDPE and LDPE

High density polyethylene HDPE and low density polyethylene LDPE are part of the polyolefins family. The HDPE volume in 2007 accounts for 23% (roughly 5 million Mg) of Western Europe's total polyolefins production which is 22.1 million Mg/year. Polyolefins represent 40% of total plastics production in Western Europe, which is 55 million Mg/year. HDPE is usually regarded as a polyethylene, produced in low pressure reactors and so is referred to as high density polyethylene. Polyolefins are produced from olefin (alkene) monomers because the olefins contain a reactive double bond. Two main techniques are used for the production of HDPE: the suspension (slurry process) and the gas phase process. HDPE is one of the most popular plastics in use today. HDPE resins can be tailored to be used in many applications such as: film, crates, boxes, caps and closures, bottles and containers for food products, cosmetics, pharmaceuticals, household and industrial chemicals, toys, fuel tanks and other automotive parts, pipes for gas and water distribution [12,13]. A process flow diagram of a typical modern suspension process (slurry process) is shown in Figure 1 [13].
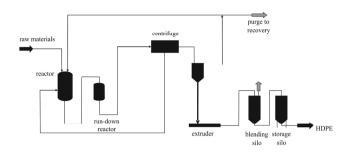

Fig. 1. Flow diagram of an HDPE production [13]

The LDPE volumes in 2007 account for 35% (roughly 7.8 million Mg per year) of Western Europe's total polyolefins production. LDPE is a polyethylene produced by a high pressure process, and it is therefore often referred to as high pressure polyethylene. The main technique which is used for the production of LDPE: Autoclave and tubular high pressure technology: when the monomer is held at high pressures of up to 30 MPa and temperatures above the polymer melting point of up to 300°C, the monomer/polymer mixture can act as a polymerisation medium. This technology is typical for LDPE and LDPE co-polymers production. The obtained polymer can be mixed with additives and is extruded into pellets. A basic flow diagram for LDPE processes is shown in Figure 2 [13].
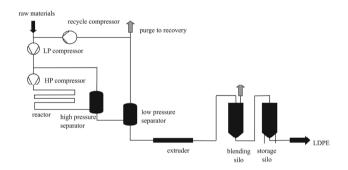

Fig. 2. Flow diagram showing LDPE production [13]

4. Eco-efficiency analysis - a case study Methods and discussion

Eco-efficiency analysis was conducted in accordance with the Central Mining Institute methodology. The mathematic notations of eco-efficiency as a combination of economic performance as DGC and ecological performance as LCA are expressed by the ratio as follows:

$$Eco-efficiency = \frac{1}{DGC \times LCA} \qquad (1)$$

This paper demonstrates eco-efficiency analysis of chosen polyolefins production. The method can be summarized in four steps:

- identify the system boundary and functional unit,
- environmental assess and select environmental performance indicators,
- economic assess and select value performance indicators,
- eco-efficiency analysis.

4.1. Environmental assessment of polyolefins production

Carry out a full LCA analysis is a complex process, hence the use of certain limitations. Impact assessment analysis has been carried out only for use stage (production stage). It excluded the impact of construction of the process plant and equipment maintenance and impact of disposal.

In order to assess the ecological risks posed by the polyolefins production feed material were analyzed in the process, but it is limited to basic materials based on inventory data contained in the reports of Best Available Techniques BAT, and the literature review [13-15]. The LCA of chosen polyolefins production is carried out using LCA software package SimaPro 7.1 (Pre Consultants B.V), with database in the program (ecoinvent) and the Ecoindicator 99 and CML 2 baseline 2000 V2.03 assessments methods. The system boundary was defined as cradle to factory gate production of these polyolefins including all inputs, raw material, energy, emissions and waste. The functional unit was set to be 1000 kg of HDPE and LDPE.

The evaluation of environmental impacts caused by the HDPE and LDPE production effects of three categories: " Human Health", " Ecosystem Quality " and " Resources" in Pt on Mg products (HDPE and LDPE) is shown in Table 1.

Table 1.
Environmental impact assessment in three categories of threats (using Ecoindicator 99 method)

Damage category	HDPE, Pt/Mg	LDPE, Pt/Mg
Human Health	64.9	78.3
Ecosystem Quality	12.9	15.9
Resources	240.8	261.7
Total	318.7	356.0

LCA analysis by using ecoindicator 99 method shows that LDPE production has more environmental impact than HDPE production. The average ecoindicator value for LDPE is 356 Pt and for HDPE is 318 Pt per 1 Mg of product. It was found that the highest impact on the environment occurs in the category of "resources" amounts 261 Pt for LDPE and 240 Pt for HDPE. The category "resources" is 75% of risks posed by these processes. The highest impact on resources is caused by ethylene production (87%).

In Table 2 was shown eleven impact categories using ecoindicator 99 assessment method for HDPE and LDPE production, in Pt on Mg products (HDPE and LDPE).

The second analysis was performed using CML 2 baseline 2000 V2.03 assessment method. Impact categories for 1Mg of HDPE and LDPE production, were seen in Table 3.

Table 2.
Environmental impact assessment in eleven impact categories

Impact category	HDPE, Pt/Mg	LDPE, Pt/Mg
Carcinogens	2.9	3.7
Respiratory organics	0.6	0.5
Respiratory inorganics	47.3	56.9
Climate change	13.6	16.5
Radiation	0.3	0.5
Ozone layer	0.2	0.2
Ecotoxicity	7.4	8.9
Acidification/ Eutrophication	3.9	4.7
Land use	1.6	2.4
Minerals	0.1	0.2
Fossil fuels	240.8	261.5
Total	318.7	356

Table 3.
Environmental impact assessment using CML method, per Mg

Impact category	Unit	HDPE	LDPE
Abiotic depletion	kg Sb eq	37.384	41.637
Global warming (GWP100)	kg CO_2 eq	2529.882	3062.441
Ozone layer depletion (ODP)	kg CFC-11 eq	0.008	0.008
Human toxicity	kg 1.4-DB eq	3107.847	3464.226
Fresh water aquatic ecotoxicity	kg 1.4-DB eq	367.840	416.545
Marine aquatic ecotoxicity	kg 1.4-DB eq	1931013	2372936
Terrestrial ecotoxicity	kg 1.4-DB eq	30.541	36.783
Photochemical oxidation	kg C_2H_4	3.469	1.989
Acidification	kg SO_2 eq	22.507	27.408
Eutrophication	kg PO_4 eq	0.880	1.023

For HDPE 2529.8 kg CO_2 equivalent is released in the atmosphere and for LDPE 3062.4 kg CO_2 equivalent, per 1Mg of product. The highest impact on CO_2 equivalent in these production is related to ethylene. The next stage of the study was LCA analysis for the ethylene production. Life cycle inventory of ethylene production was developed based on literature data [13,14,16]

Ethylene is the most important base chemical in the petrochemical industry. One alternative route for the production of ethylene is from natural gas via oxidative coupling of methane. So far the process is economically unfeasible. However, recent studies suggest that this may be overcome by producing not only ethylene but also electricity, using the heat from the very exothermic coupling reaction. Ethylene can be converted industrially into a variety of intermediate and end products. The major use of ethylene is conversion to low-and high-density polyethylenes (HDPE and LDPE). Ethylene products from hydrocarbons consist basically of four operations: the thermal

cracking, quenching, gas compression/treatment, ethylene purification, and refrigeration. Ethylene is produced, together with a variety of co-products, by the steam cracking of naphtha or natural gas liquids. The natural gas liquids contain ethane, butane and propane and when they are pyrolysed the products are ethylene and propylene. Ethylene production via steam cracking is a basic chemical process.

Emissions from ethylene production are released to air and water. They consist primarily of ethylene and propylene emissions to air, and methanol and propane/butane emissions to water. In the case of ethylene, naphtha occupies a major part in all impact categories, especially Photochemical Ozone Creation Potential (POCP). This is mainly due to the processing of crude oil, which causes VOC emissions [18].

Based on analysis of the LCA found that the highest impact on the environment in the production of ethylene is naphtha refinery (almost 70%). For 1Mg ethylene production CO_2 equivalent is 2180 kg CO_2 eq.

Economics and environmental issues are the dominant factors considered in the choice of feedstock and processes of ethylene production. In the past forty-five years, there have been some improvements and advances within the conventional ethylene production technology. In thermal cracking, researchers worked on increasing product yield, feedstock flexibility, and thermal efficiency. In purification and recovery, there has been progress in different unit operations such as in distillation, refrigeration, and separation [16,17].

4.2. Economic assessment of chosen polyolefin production

For the purposes of this article uses data on the economic parameters of the production of polyethylene, published as the Best Available Techniques, which is in accordance with the standards set by the IPPC Directive (Integrated Pollution Prevention and Control). Available values for the studied LDPE production technology (production technology: turbular) and HDPE (production technology: gas phase) are summarized in Table 4.

Table 4.
Overview of the production costs for the chosen production processes of polyethylene [13]

Description	LDPE	HDPE
Total plant capital, USD	141 000 000	108 000 000
Total production costs with depreciation, USD/Mg	733	770
Total production costs with depreciation, USD/year	219 900 000	154 000 000
Depreciation, USD/Mg	59	68
Production, kt/year	300	200
Operation period, year	15	15
Price, USD/Mg	1 000	1 000
Receipts, USD/year	300 000 000	200 000 000

Based on the above statement may be noted that available data were established for different production volumes. For this

reason, decided to apply the calculation method for calculating the rate of DGC (Dynamic Generation Cost). This is an indicator developed and used in the German bank KfW [19]. Dynamic unit cost is equal to the price, which allows for discounted revenues equal discounted costs. DGC shows what is the cost of the technical unit of the product - in this case the PE. Because it ignores the revenue, and includes the cost of investment and operational phases (life cycle), its value reflects the cost per life-cycle of the analyzed product/technology. Table 5 shows the calculation of the indicator DGC and discounted costs for the life cycle of the analyzed technologies.

DGC ratio can be calculated from formula:

$$DGC = \frac{\sum_{t=0}^{t=n} \frac{KI_t + KE_t}{(1+i)^t}}{\sum_{t=0}^{t=n} \frac{P_t}{(1+i)^t}} \tag{2}$$

where:
KI$_t$ - capital costs incurred during the year;
KE$_t$ - operating costs incurred during the year;
P$_t$ - production in the year;
i   - discount rate;
t   - year, ranges from 0 to n, where 0 is the year of the first bear the costs, while "n" is the last year of installation.

Table 5.
Calculation of the DGC and discounted costs for the life cycle

Description	LDPE	HDPE
Discounted investment costs, USD	134 392 290	102 938 776
Discounted operation costs, USD	2 811 118 739	1 968 677 971
Discounted investment and operation costs – LCC, USD	2 945 511 030	2 071 616 747
NPV, USD	1 318 668 934	731 528 345
DGC, USD/Mg	768	810

Analyzing the above results can be observed discrepancies in the sizes obtained: the technology indicator DGC LDPE is lower than for HDPE technology, while the NPV indicators and LCC adopt a higher value. This is the scale of the event: the production of two different sizes of installations. Given the investment, operating costs and production volumes, it appears that the production of LDPE is individually more efficient economically than the production of HDPE. The results obtained DGC indicator calculation will be used to eco-efficiency with LCA analysis.

Mostly often are not available operational data for the various technologies with the installation of the same capacity, applied to the DGC appear in this case the best solution in order to obtain comparable results. Scaling the available cost data (investment, operating costs) to the expected size of the system, is often impossible.

4.3. Eco-efficiency analysis

Based on the results of partial analysis of LCA and DGC was calculated using the formula (1) eco-efficiency indicators for both polymers. A higher value of indicator means a higher eco-efficiency. The results are shown in Table 6.

Table 6.
Calculation results of the eco-efficiency analysis

Using of LCA method	Eco-efficiency	
	HDPE	LDPE
Ecoindicator 99	$3.87 \cdot 10^{-6}$	$3.66 \cdot 10^{-6}$
CML method Global warming (GWP100)	$4.88 \cdot 10^{-7}$	$4.25 \cdot 10^{-7}$

The obtained results of calculations using both LCA methods indicate higher eco-efficiency of HDPE production. Moreover relative eco-efficiency values for two polyolefins, where economic performance is measure as DGC, and environmental impact is measured in Pt, is shown in Figure 3. Environmental impact measured in greenhouse gases emission as CO_2 eq (CML method) is presented in Figure 4.

Also, this way to present the results of LCA and DGC analysis allows to compare eco-efficiency of technologies tested. The results indicate higher eco-efficiency of HDPE technology.

5. Conclusions

The objective of this work was to present the eco-efficiency methodology and evaluate together the economic and environmental indicators of HDPE and LDPE production. In this article the influence of HDPE and LDPE production on the environment and economic performance was carried out by using Life Cycle Assessment (LCA) and Dynamic Generation Cost (DGC). Conducted environmental analysis of chosen polyolefins production have shown that the highest environmental impact is in the category of "resources" and is linked fossil fuel (ethylene production).

Ethylene production has large economic and environment impact. This is required new processes for ethylene production. In the future research it will be conducted to compare analysis of economic and environmental performance of all processes of ethylene production using different feedstocks.

For the calculation of cost indicators were used available data on capital expenditure and operating costs of selected technologies of polyethylene production. Because the data were available for different sizes of production, it was decided to use DGC index in the analysis. This index shows the technical cost of obtaining unit of the product. Using DGC and LCA analysis were calculated eco-efficiency, which allows to compare production technologies of chosen polyolefins, and it was adopted methodology for eco-efficiency calculating. It was not performed comparison to references technologies, that is why the results allow only a statement, which technology is more eco-efficient.

In interpreting the results should be considered a source of data made in the calculation: Best Available Techniques in the Production of Polymers. Therefore, it can be concluded that

eco-efficiency indicators presented in this paper could be used as a benchmark for eco-efficiency assessment of polyethylene production by chosen technologies in existing installations.
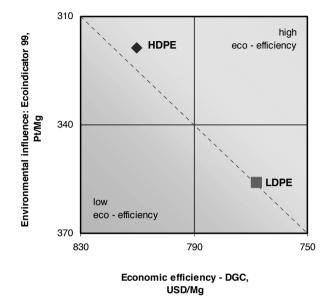

Fig. 3. Relative eco-efficiency values measured by DGC and Ecoindicator 99 methods
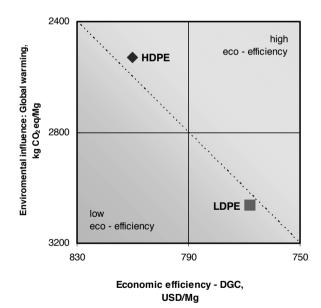

Fig. 4. Relative eco-efficiency values measured by DGC and CML (calculated as CO_2 eq) methods

Acknowledgements

References

[1]   O. Michelsen, A. M. Fet, A. Dahlsrud, Eco-efficiency in extended supply chains: A case study of furniture production, Journal of Environmental Management 79 (2006) 290-297.

[2]   R. Co, A. Booth, B. Louis, Eco-efficiency and SMEs in Nova Scotia Canada, Journal of Cleaner Production 14 (2006) 542-550.

[3]   World Business Council for Sustainable Development, Ecoefficiency: creating more value with less impact, Geneva 2000.

[4]   http://www. wbcsd.org/

[5]   M.M. Thant, K. Charmondusit, Eco-efficiency assessment of pulp and paper industry in Myanmar, Clean Technologies and Environmental Policy 12 (2010) 427-439.

[6]   H.A. Verfaillie, R. Bidwell, Measuring Eco-Efficiency – A Guide to Reporting Company Performance, World Business Council for Sustainable Development, 2000.

[7]   K. Czaplicka-Kolarz, J. Wachowicz, M. Bojarska-Kraus, A Life Cycle Method for Assessment of a Colliery Colliery's Balance, The International Journal of Life Cycle Assessment 9 (2004) 247-253.

[8]   K. Czaplicka-Kolarz, M. Ściążko, Model of ecological and economic forecasts of clean coal production and utilization, Central Mining Institute, Katowice, 2004 (in Polish).

[9]   EN ISO 14040:2006 Environmental management. Life cycle assessment. Principles and framework.

[10] W. Rogowski, Account of investment efficiency, Kluwer Poland, Cracow, 2008 (in Polish).

[11] G. Rebitzer, D. Hunkeler, Life cycle costing in LCM: ambitions, opportunities, and limitations Discussing a framework, The International Journal of Life Cycle Assessment 8 (2003) 253-256.

[12] PlasticsEurope: Annual Report 2007, Safeguarding the planet by reaching out, Brussels, 2007.

[13] Reference Document on Best Available Techniques in the Production of Polymers. European Commission, Joint Research Centre, 2006.

[14] D. Saygın, M.K. Patel, C. Tam, D.J. Gielen, Chemical and Petrochemical Sector, Potential of best practice technology and other measures for improving energy efficiency, OECD/IEA, September, 2009.

[15] K.G. Harding, J.S. Dennis, H. von Blottnitz, S.T.L. Harrisom, Environmental analysis of plastic production processes: Comparing petroleum-based polypropylene and polyethylene with biologically-based poly-hydroxybutyric acid using life cycle analysis, Journal of Biotechnology 130 (2007) 57-66.

[16] J.A. Hugill, F.W. Tillemans, J.W. Dijkstra, S. Spoelstra, Feasibility study on the co-generation of ethylene and electricity through oxidative coupling of methane, Thermal Engineering 25 (2005) 1259-1271.

[17] M. Baitz, S. Albrecht, S. Deimling, M. Goymann, Environmental and economic analysis of different synthesis routes for ethylene, PE INTERNATIONAL GmbH. Leinfelden–Echterdingen, Germany, 2007.

[18] C. Hendriks, D. Papameletiou, Strategies on the future of the chlorine industry, IPTS Report, 1996.

[19] J. Rączka, Cost-efficiency analysis based on dynamic rate of unit cost. Training materials developed under the Transform Advice Programme - Investment in Environmental Infrastructure in Poland, 2002 (in Polish).

[20] R. Nowosielski, M. Spilka, A. Kania, Methodology and tools of ecodesign, Journal of Achievements in Materials and Manufacturing Engineering 23/1 (2007) 91-94.