MONITORING THE IMPACTS OF THE RECYCLING INDUSTRY – THE LCA ANALYSIS

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Summary: The present article discusses the possible use of life cycle assessment (LCA) technique to estimate the environmental impacts of the recycling process. The first part of this article is strictly devoted to methodological aspects of LCA and recycling of wastes, including the diagnosis of the situation in the recycling industry in Poland. The second part of the article describes a case study of the LCA analysis of dry waste recycling in the city of Kielce.

Keywords: life cycle assessment (LCA), waste, recycling, industrial ecology, innovative management

1. Introduction

Life cycle assessment (LCA) is a multi-stage procedure for calculating the environmental impacts of a product or process. It allows for the determination in which part of the analysed action, process and operation specific environmental threats occur, which subsequently enables to select effective ways of eliminating them. It is a method recommended by Polish and European law for application in a number of various service and industrial branches, including the recycling industry. The verification of recycling processes by the means of LCA method may allow for the maintenance of high quality of all actions connected with the re-use of waste products, which is of considerable significance in the conditions of limited natural resources and the degradation of the environment.

2. The essence and stages of LCA

Life-cycle assessment (LCA) is a powerful tool to assess environmental impacts associated with a product or process in all phases of the life cycle. In other words, the LCA analysis examines the relationships between the product or process and the surrounding environment. Environmental impact is due to consuming natural resources or introducing harmful elements into the environment [1]. Regulated by the ISO 14040 series standards and the corresponding Polish equivalents (PN-EN 14040:2009 Environmental management – Life cycle assessment – Principles and framework [2] and PN-EN 14044:2009 Environmental management – Life cycle assessment – Requirements and guidelines [3]), LCA consists in four basic stages:

1. goal and scope definition;
2. life cycle inventory (LCI);
3. life cycle impact assessment (LCIA);
4. interpretation.

Goal and scope definition is a key step of the life cycle assessment (LCA) that incorporates a number of successive operations; the most important are [4]:

– determining the goal of the analysis,
– defining the product system and the functional unit,
– determining the boundaries of the system.

The goal and scope of the study has to be clearly defined, because it determines and guides the choices to be made in the other phases of the study. The product system is "set of material and energy connected unit processes that fulfil one or more defined functions" [5]. The functional unit relates to the given function of the product and provides a reference to which the inputs and outputs can be related. The system boundary determines, which unit processes ought to be included in the LCA analysis [4].

Life cycle inventory (LCI) consists of detailed tracking of all inputs and outputs for a given product system throughout its life cycle, including raw resources or materials, water, energy and fuel, solid waste, air and water emissions**.** This analysis may involve dozens of individual unit processes (e.g., the extraction of raw resources, various primary and secondary production processes, transportation, etc.) and the inputs and outputs are assigned to each unit process.

Life cycle impact assessment (LCIA) is divided into the following mandatory steps [4]:
– selection of impact categories, category indicators and characterization models,
– classification, i.e. assignment the individual inventory parameters to specific impact categories,
– characterisation, i.e. conversion of LCI flows to common units within each impact category, so that results can be summed to provide an overall impact category indicator.

Interpretation involves the process of identifying, quantifying, checking and evaluating the information resulting from the life cycle inventory (LCI) and impact assessment (LCIA) phases. The outcome of the interpretation phase is a set of conclusions, limitations and recommendations for future studies.

3. Waste recycling

Recycling is the process of recovering materials and substances found in waste and turning them into new products, sometimes completely different in form from their original state. Definition of recycling included in the Act of 14 December 2012 on Waste states that it is the process of changing waste in „products, materials or substances for primary or other use; it includes reprocessing of organic material (organic recycling), but it does not include recovering energy and reprocessing it into materials, that will be used as fuels or for filling in excavations" [6]. Recycling is one of key methods of environmental protection, because its purpose is to reduce waste and consumption of natural resources. The idea behind it is to reclaim as many substances and materials as possible from segregated waste, and at the same time limit the resources necessary for waste treatment [7]. Recycling is one of the forms of recovery that shall mean „any process, which aims to beneficial use of waste by replacing other materials, which would otherwise be used for the same purpose, or as result of which the waste is prepared to fulfil the same function in the given business or in the economy in general" [6].

The process of recycling can be applied to different products and materials, which belong to municipal wastes (most often: paper, glass, different metals, plastic, textiles), post-usage wastes (for example batteries, electrical and electronic equipment, end of life vehicles) and industrial wastes (from production process, including hazardous wastes). Waste may be processed into useful products, namely products from secondary-raw materials, or with the use of secondary-raw materials (so called material recycling or mechanical recycling) or it may be processed into raw material to be used to manufacture a given product (so called feedstock recycling or chemical recycling) [8, 9]. Process of material or chemical recycling includes the following stages [8, 10, 11]:

1. Obtaining waste - gathering municipal wastes, post-usage wastes and industrial wastes.
2. Treatment of waste - may include the following operations:
   - segregation - separating different kinds of waste,
   - shredding - decreasing the size of the waste down to several mm,
   - cleaning - washing the waste in water with detergents, spinning and drying the waste,
   - further processing - depending on the kind of obtained waste.
3. Processing of secondary-raw materials.

Major benefits of recycling include [7, 12, 13, 14]:

- limiting the use of primary raw materials, which protects natural recourses,
- decrease in the amount of waste and space need to store waste as well as the cost of storing waste for local governments,
- decrease in the use of energy in the process of secondary production in comparison to manufacturing with the use of primary raw materials (e.g. decrease in the use of energy in process of recycling one ton of steel by 84%),
- reduced water and air pollution (e.g. recycling one ton of paper decreases water pollution by 35% and air pollution by 74%, and recycling one ton of aluminium decreases water pollution by 97% and air pollution by 95%).

EU provisions regulate the issues concerned with the recycling of waste and the member countries, including Poland, are obliged to both implement and apply them. The European Commission’s aim is to introduce in EU countries the so-called closed cycle economies, that is such economies in which reusing, repairing and recycling will be a standard, which, on the one hand, will allow for the decrease in the environment burden, and on the other hand, will enhance the EU’s competitiveness on the markets worldwide. The competitive advantage may be accomplished as a result of the introduction of innovations in the materials obtained by the means of recycling, product innovations for example products with better parameters and the longer usage period, as well as technological innovations that will enable to change wastes in resources with higher efficiency [15].

Poland is a country with enormous potential for companies active in the recycling branch, which results from legal requirements imposed by the EU, that impose increasing the role of recycling. Therefore, the level of recovery and recycling in Poland will increase year after year, especially since, in accordance with the European Commission’s guidelines, by 2030 the European will have recycled 70% of the municipal wastes and 80% of the packaging wastes, and starting from 2025 it will be forbidden to store wastes that can be recycled. According to the data provided by the Central Statistical Office in 2012 in Poland there were 314 kg municipal wastes for one inhabitant, and only 13% of these wastes were recycled (the EU average was 27%) [16,17]. At the same time the level of recycling of packaging wastes amounted for 41,4%. High recycling levels were obtained for the Waste Electrical and Electronic Equipment (WEEE), for instance, large and small household appliances it was correspondingly 91% and 84%, consumer equipment – 88%, IT and telecommunications equipment – 87%. In the case of vehicles withdrawn from operation and handed over to a dismantling facility, 83% of their total mass was subjected to recovery and recycling. According to the Central Statistical Office the recovery level of industrial wastes (recycling included) amounted for 72,3% [17].

Recycling efficiency mostly depends on a well-organized waste collection and segregation. It is important to form ecological awareness of the Polish society, for example, to inform them about the consequences of throwing away wastes in the places not suited for such purposes and to introduce proper legal solutions, e.g. to forbid the acceptance of electronic wastes at scrapyards, which might contribute to the improvement of the recycling rates. In order to increase the recycling level one might apply a range of instruments, such as landfill bans on biodegradable waste or municipal waste that has not been pre-treated, mandatory selective collection of municipal waste fractions, as well as instruments of economic nature, for example, taxes from storing and burning, and waste collection fees incentivising recycling [18].

4. LCA analysis of dry waste recycling – the case study of the city of Kielce

The city of Kielce (*Civitas Kielcensis)* is a medium size city, inhabited approximately by 198 000 people, located in the southern part of central Poland in the Świętokrzyskie Region. To fulfil the legal requirements, the city of Kielce was allocated to the 4th municipal waste management region, inhabited by app. 390 000 people. The predominant type of housing in the city is high rise housing inhabited by 63% of population, the remaining ones are detached housing inhabited by 27% of population and tenement housing inhabited by 10% of population [19]. It is approximately 54 000 Mg of municipal waste generated in Kielce yearly that gives 275 kg per person [20]. In 2013, the level of re-use and recycling of paper, metal, plastics and glass was estimated at 19%.

4.1. Goal and scope

The predominant goal of the analysis is to investigate the environmental impacts of dry waste recycling process in the city of Kielce. Only by monitoring the impacts, one can assess the sustainability of the waste management system – if the system is environmentally positive or negative. Sample indicators of the environmental sustainability are the conservation of natural resources, air emissions, fuel or electricity consumption, noise [21].

The scope of the analysis covers the recycling process of dry waste (paper, metal, plastics and glass) in the city of Kielce. Due to the fact that, at present, only waste from the high-rise housing of Kielce (63% of population) is directed to the recycling, the analysis is simplified to this type of housing. The remaining waste, even though collected selectively at source, is stored and awaits for the opening of the regional installation for waste treatment in Promnik at the end of 2015. Municipal waste in the regional installation in Promnik, of the maximum capacity of 150 000 Mg per year, will undergo multi-stage mechanical-biological treatment.

The process of recycling was divided into the following unit processes:

- waste generation,
- sorting at home,
- eco-logistics (collection and transport),
- waste segregation in the material recovery facility (MRF),
- secondary raw material transport,
- reprocessing (see figure 1).

The functional unit is the total amount of waste generated in the city of Kielce in 2012, expressed in kg. Such identification of the functional unit enables different waste management systems to be treated as functionally equivalent and allows reference flows to be determined.

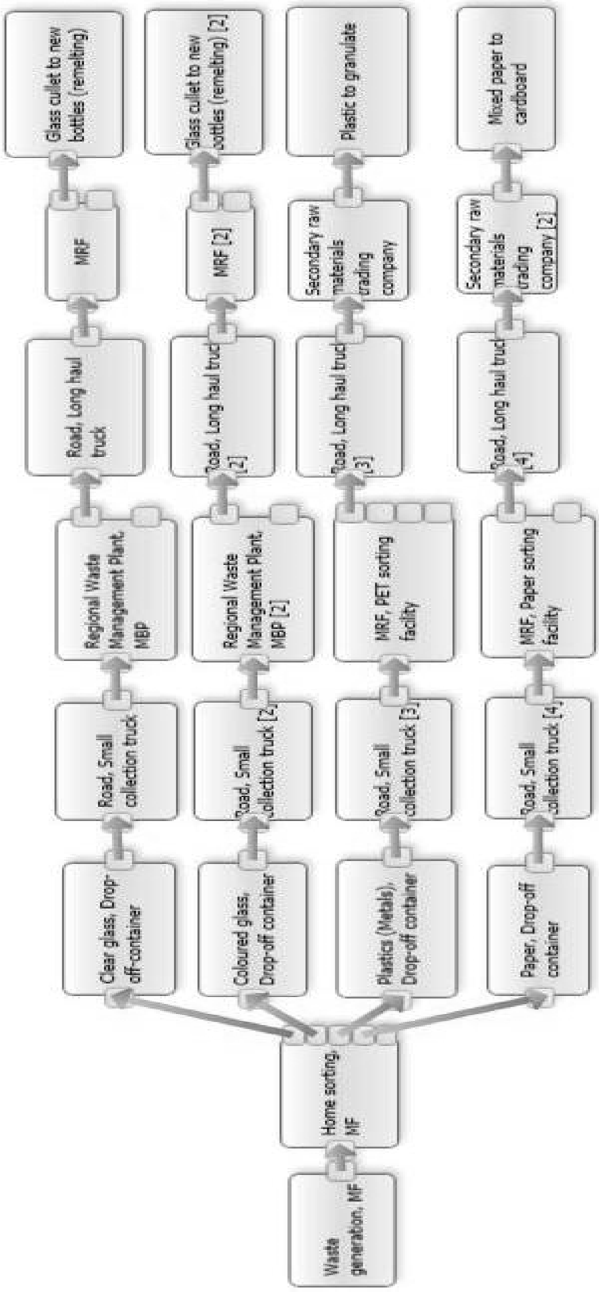

Fig. 1. The system boundary for the recycling process of dry waste in the city of Kielce
Source: Own research

4.2. Inventory analysis

To perform the LCIA analysis, a number of quantitative and qualitative data on dry waste management in the city of Kielce are to be collected. They cover, among others,:

- the amount of waste generated in the city of Kielce yearly,
- the morphological composition of waste in the city of Kielce (see figure 2),
- waste collection systems,
- fuel consumption during waste collection and transportation,
- the sorting efficiency of MRF,
- reprocessing technologies of the secondary raw materials,
- the levels of reuse and recycling of paper, metal, plastics and glass,
- the levels of bio-waste landfilling in relation to the weight of the bio-waste produced in 1995.

Unless had been possible to collect the relevant data on dry waste recycling, the data would have been taken from the LCA software (see figure 3).

Total amount (kg) 5.404E+07

Include upstream impacts

Add fraction | Normalise composition to 100%

Material fraction	%
Clear glass	2.53
Plastic bottles	2.13
Plastic, Greenland	15.93
Textiles	2.48
Wood	0.37
Vegetable food waste	33.88
Paper and carton containers	23.97
Aluminium foil and containers	0.73
Metal - Non Aluminum, Greenland	1.86
Batteries	0.26
Soil	10.8
Green glass	2.53
Brown glass	2.53

Fig. 2. Data inventory – the quantity and composition of municipal waste in Kielce
Source: Own research

Plastic to granulate

External processes

Add external process

Name	Amount	Unit	Per	Comment
Fuel Oil (Light) in Industry Burner (prod + comb), 1-100MW, DK, 1990	1.1/1000	kg	kg Total Wet Weight	
Electricity Production, SE, 2001	0.088	kWh	kg Total Wet Weight	
Production and Combustion of Diesel Oil in Truck, EU2, 1998	0.00213	kg	kg Total Wet Weight	
Polyethylene high density granulate (PE-HD), RER, ELCD, 1999 - corrected	-0.97	kg	kg Total Wet Weight	
Fuel Oil (Light) in Industry Burner (prod + comb), 1-100MW, DK, 1990	0.0011	kg	kg Total Wet Weight	

Elementary exchanges

Add elementary exchange

Name	Compartment	Sub compartment	Amount	Unit	Per	Comment
Carbon dioxide, fossil	air	unspecified	3.6/1000	kg	kg Total Wet Weight	
Sulfur dioxide	air	unspecified	0.0011/1000	kg	kg Total Wet Weight	
BOD5, Biological Oxygen Demand	water	surface water	1.9/1000	kg	kg Total Wet Weight	
Cadmium, ion	water	surface water	6.1E-10	kg	kg Total Wet Weight	
COD, Chemical Oxygen Demand	water	surface water	21/1000	kg	kg Total Wet Weight	
Nitrogen	water	surface water	0.003/1000	kg	kg Total Wet Weight	
Phosphorus	water	surface water	0.001/1000	kg	kg Total Wet Weight	
TOC, Total Organic Carbon	water	surface water	6.4/1000	kg	kg Total Wet Weight	

Fig. 3. Data inventory – the environmental indicators of the plastic reprocessing technology
Source: Own research

4.3. Life cycle impact assessment

In this phase of LCA, the multitude of environmental data, collected in the inventory analysis, are characterised. Consequently, all environmental impacts are classified in a system of impact categories (for instance climate change, human toxicity, eutrophication), which are described by category indicators (for instance kg CO_2 - Eq, CTU, kg P - Eq) (see table 1). Subsequently, during normalisation the results of characterisation are divided by a reference value (see figure 4). The person equivalent (PE), which means the annual impact from an average person of a given region (Europe), is a commonly applied reference value. The positive values of normalisation indicate environmental burden, while the negative values of normalisation represent environmental benefits.

Although there are various LCIA methods applied in the LCA studies of waste management (for instance IPCC 2007, EDIP 97/2003, Eco-indicator 99), ILCD 2013 was selected for the research of the recycling process for the city of Kielce. It is, though, broadly recommended for this type of studies, among others by the Joint Research Centre of the European Union.

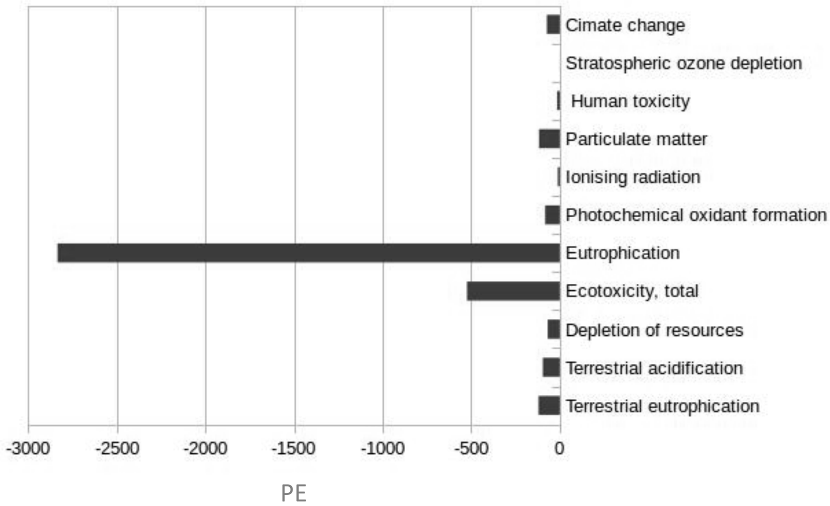

Fig. 4. Normalised environmental impact profile of the recycling process of dry waste in Kielce
Source: Own research

Results of the conducted LCA analysis of the recycling process of dry waste in Kielce proved that wisely performed the process of re-use and recycling leads to a number of environmental benefits and thus satisfies the waste hierarchy. Normalisation values are negative in all categories of impact, although not to the same extent. The greatest profits occur in terms of eutrophication and ecotoxicity. As these are both output related categories, this might suggest that there are relatively low environmental emissions, especially phosphates and nitrates, to all compartments of the environment. Regarding the stages of the recycling process, waste collection at homes and waste segregation in the material recovery facility (MRF) are the sources of the largest environmental burdens.

Tab. 1. Characterised environmental impact profile of the recycling process of dry waste in Kielce (Source: Own research)

Name	Climate change	Stratospheric ozone depletion	Human toxicity	Particulate matter	Ionising radiation	Photochemical oxidant formation	Eutrophication	Ecotoxicity, total	Depletion of resources	Terrestrial acidification	Terrestrial eutrophication
Characterisation impact	kg CO2	kg CFC-11	CTU	kg PM2.5	kg U235	kg NMVOC	kg P/N	CTU	MJ	AE	AE
Sum	**-5,91E+05**	**-0,005587**	**-1,48E-02**	**-322**	**-1,45E+04**	**-4664**	**-2,62E+04**	**-3,48E+05**	**-4,24E+06**	**-4733**	**-1,38E+04**
Regional Waste Management Plant, MBP	4075	1,25E-06	3,62E-05	0,4283	3,414	4,672	1,62E+00	8,582	4,52E+04	5,695	17,84
Clear glass, Drop-off-container	3772	3,61E-06	2,89E-05	0,9133	9,467	34,89	1,24E+01	98,05	5,02E+04	26,21	135,8
Plastics (Metals), Drop-off container	3,08E+04	2,95E-05	2,36E-04	7,454	77,27	284,8	1,01E+02	800,2	4,10E+05	214	1109
Road, Small collection truck	923,8	8,85E-07	7,09E-06	0,2237	2,319	8,544	3,04E+00	24,01	1,23E+04	6,42	33,27
Road, Small collection truck [3]	3016	2,89E-06	2,31E-05	0,7302	7,569	27,89	9,92E+00	78,39	4,01E+04	20,96	108,6
Road, Long haul truck	2286	2,19E-06	1,75E-05	0,5019	5,738	18,02	6,35E+00	59,43	3,04E+04	13,66	69,52
MRF	4035	1,24E-06	3,58E-05	0,424	3,38	4,625	1,61E+00	8,497	4,48E+04	5,638	17,66
Road, Long haul truck [4]	3247	3,11E-06	2,49E-05	0,713	8,152	25,6	9,02E+00	84,42	4,32E+04	19,41	98,76
Glass cullet to new bottles (remelting)	-6,87E+04	2,68E-05	-5,21E-04	-39,05	75,17	-353,4	-1,08E+02	-2723	8,84E+05	-476,2	-1582
Coloured glass, Drop-off container	7544	7,23E-06	5,79E-05	1,827	18,93	69,78	2,48E+01	196,1	1,00E+05	52,43	271,7
Road, Small collection truck [2]	1848	1,77E-06	1,42E-05	0,4473	4,637	17,09	6,07E+00	48,02	2,46E+04	12,84	66,53
Regional Waste Management Plant, MBP [2]	8151	2,50E-06	7,24E-05	0,8566	6,829	9,343	3,25E+00	17,16	9,04E+04	11,39	35,68
Road, Long haul truck [2]	4572	4,38E-06	3,51E-05	1,004	11,48	36,04	1,27E+01	118,9	6,08E+04	27,33	139
MRF [2]	8069	2,48E-06	7,16E-05	0,848	6,761	9,25	3,22E+00	16,99	8,95E+04	11,28	35,33
Glass cullet to new bottles (remelting) [2]	-1,37E+05	5,35E-05	-1,04E-03	-78,1	150,3	-706,9	-2,17E+02	-5447	1,77E+06	-952,4	-3165
Paper, Drop-off container	3,57E+04	3,42E-05	2,74E-04	8,65	89,66	330,4	1,17E+02	928,5	4,75E+05	248,3	1286
Road, Small collection truck [4]	3499	3,35E-06	2,68E-05	0,8473	8,783	32,37	1,15E+01	90,96	4,65E+04	24,32	126
MRF, Paper sorting facility	1,83E+04	4,03E-06	1,77E-04	1,778	24,15	30,11	1,07E+01	322,8	1,28E+05	44,75	118,1
MRF, PET sorting facility	3,33E+04	1,02E-05	2,95E-04	3,496	27,87	38,13	1,33E+01	70,05	3,69E+05	46,48	145,6
Road, Long haul truck [3]	288,6	2,77E-07	2,21E-06	0,06336	0,7244	2,275	8,01E-01	7,502	3838	1,725	8,775
Secondary raw materials trading company [2]	3,82E+04	1,17E-05	3,39E-04	4,015	32,01	43,8	1,52E+01	80,47	4,24E+05	53,4	167,3
Secondary raw materials trading company	3395	1,04E-06	3,01E-05	0,3568	2,845	3,892	1,35E+00	7,15	3,77E+04	4,745	14,86
Mixed paper to cardboard	-2,01E+05	-0,005798	-1,46E-02	-143,4	-1,51E+04	-2839	-2,60E+04	-3,44E+05	-9,06E+05	-2559	-1,02E+04
Plastic to granulate	-3,99E+05	2,97E-06	-3,98E-04	-97,02	7,771	-1796	-2,56E+02	1210	-8,51E+06	-1596	-2807

5. Conclusions

Discussed in the article analysis of dry waste recycling for the city of Kielce demonstrated high capacity of life cycle assessment (LCA) for planning, optimising and comparing various recycling systems. Notwithstanding, LCA supports the innovative management and enables to reduce the risks of mismanagement of recycling processes, and related to it serious environmental, economic and social consequences. It can, hence, be assumed that in the near future LCA will become a leading environmental management technique of the production engineering, integrated with ISO 9001 and ISO 14001.

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