Chapter 1

Benefits of 3R: From a Life Cycle Perspective

Thumrongrut Mungcharoen
Faculty of Engineering, Kasetsart University, Thailand.
National Metal and Materials Technology Center, Thailand.

Sataporn Sridowtong
Faculty of Engineering, Kasetsart University, Thailand.

Worayut Saibuatrong
Faculty of Engineering, Kasetsart University, Thailand.

March 2010

This chapter should be cited as
Mungcharoen, T., S. Sridowtong and W. Saibuatrong (2010), 'Benefits of 3R: From a Life Cycle Perspective', in Kojima, M. (ed.), *3R Policies for Southeast and East Asia*. ERIA Research Project Report 2009-10, Jakarta: ERIA. pp.1-21.

CHAPTER 1

Benefits of 3R: From a Life Cycle Perspective

Thumrongrut Mungcharoen[a,b]*, Sataporn Sridowtong[a], and Worayut Saibuatrong[a]

[a] Faculty of Engineering, Kasetsart University, Bangkok 10900, Thailand

[b] National Metal and Materials Technology Center, Pathumthani 12120, Thailand

*E-mail: fengtrm@ku.ac.th, thumrong@mtec.or.th

Abstract

Depletion of mineral resources such as petroleum, aluminum and steel is one of the major problems in the world. 3R measures including resource recycling are very important practices for community and industrial activities. Life cycle assessment (LCA) is a scientific-based tool and can be used for quantitative assessment or for comparison of the environmental burdens for processes, products and 3R system by considering the whole life cycle perspective. The objective of this study is to quantitatively illustrate the benefits of 3R, especially recycling (plastic, paper, glass and metal) by using LCA methodology. Related publications and database in several LCA software programs were reviewed and calculated. The results of the study clearly show that 3R measures including resource recycling had a net gain on environmental benefits. In almost all cases, they perform better than the end-of-pipe treatment methods such as landfill and incineration in terms of life cycle reduction of greenhouse gas emission, energy consumption, and other environmental impacts.

1. Introduction

In waste management, the critical environmental impact issues do not only refers to the safe treatment and disposal of wastes but also the system management of greenhouse gas (GHG) generation [1]. 3R measures are effective solutions for waste generation and depletion of natural resources caused by the mass production and mass consumption of the present highly civilized social system. The recycling normally offers immense potential to enhance resource management and reduce waste disposal. Resource recycling helps to prolong the lifespan of landfills and reduce the need for costly incineration. It also slows down natural resource depletion to ensure sustainable development of resource-intensive industries. The use of recycled materials as a substitute for raw materials also drives down the latter’s costs [2]. Among 3R, reduce and reuse measures are obviously beneficial in all environmental aspects. However, recycling operations generally required additional processes which need more energy and/or resources before those recycled materials/products can be used again. In order to illustrate whether recycling is a good choice or not, Life Cycle Assessment (LCA) will be used to quantify the environmental burdens generated for the entire life cycle of the recycling system [3]. Various recent LCA studies on the benefits of recycling and recovered materials are reviewed. Several LCA software programs, namely SimaPro, GaBi, and JEMAI-LCA Pro, are also used for this study. The aim of this study is to illustrate the benefits of recycling by comparing the recycled materials (i.e. plastic, paper, glass and metal) to the virgin materials.

2. Framework of Life Cycle Assessment of Recycling

Recent publications related to LCA on recycling of materials showed some common characteristics on framework of analysis. These studies were used as examples to discuss the benefits of recycling and the usefulness of LCA for quantifying the environmental impact focusing on energy consumption and greenhouse gas emissions. LCA is a systematic method for evaluating the environmental burdens associated with a product, process or activity, by identifying and quantifying energy and materials consumed and wastes released to the environment [4].

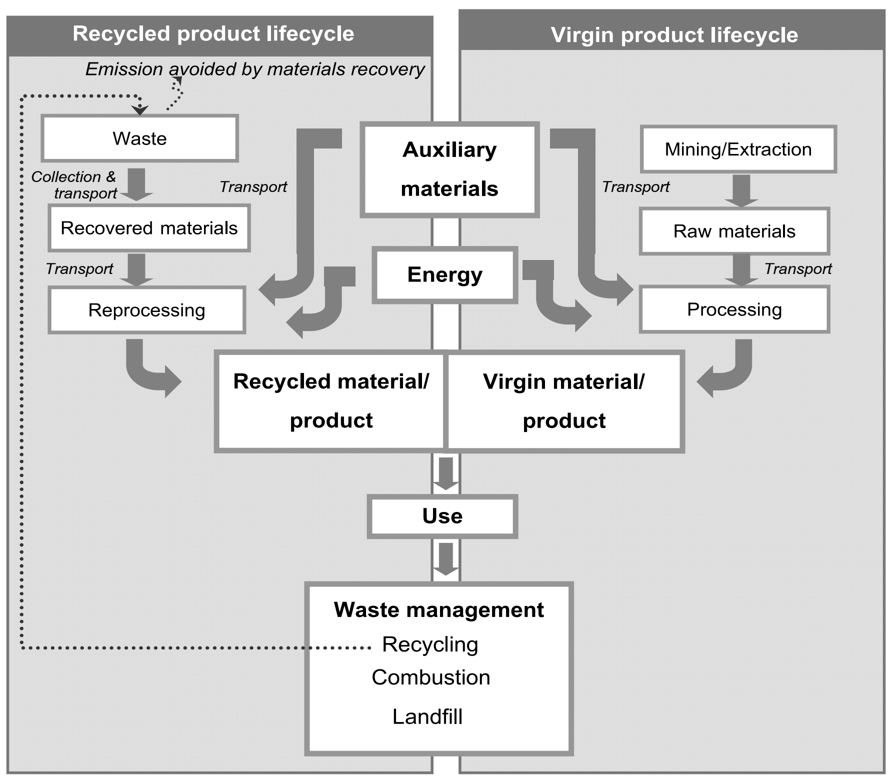


Figure 1: System boundary of the recycled and virgin material/product

Based on the scope of the LCA for recycled materials/products comparing to virgin materials/products, the system boundary for supply chain model is shown in Figure 1. In the recycled material/product, the life cycle stages for which the emission data will be gathered are recycled material collection, reprocessing (including auxiliary materials and electricity), transportation, use, and waste management. For the virgin material/product, the life cycle stages are raw material extraction, processing (including auxiliary materials and electricity), transportation, use, and waste management.

3. Benefits of Recycling

Based on the analysis of previous publications and various LCA software programs, this section presents the benefits of material recycling focusing on the greenhouse gas emissions and energy consumption reduction potential.

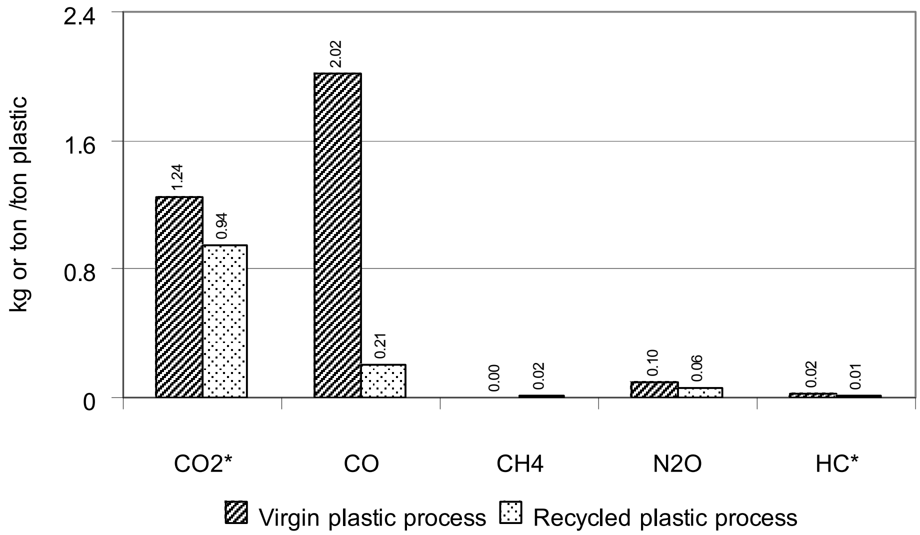
3.1 Benefits of Recycling: Based From Previous Publications

Recycling of material has been analyzed from a life cycle perspective in a number of studies over the past 15 years. Global warming impact and total energy consumption of recycled materials versus virgin materials (including plastic, paper, metal, and glass) are shown in the paragraphs below.

For plastic recycling Oil is the basic feedstock of plastics. About 4 % of crude oil is used in plastics manufacturing. Recycling of plastics can reduce the use of raw materials and energy in the virgin plastic production process and also the greenhouse gas emissions originating from waste plastics combustion. Littering problems arising from waste plastics would also diminish [5]. Some of the previous studies which have reported various benefits of plastic recycling are the following:

Molgaard C. (1995) studied the environmental impacts by disposal of plastic from municipal solid waste (consists mainly of HDPE, LDPE, PP, PS, PET and PVC). The investigation performed was the material recycling process containing a section for pre-washing, a section for separation of plastic into its generic types, a section for precutting (shredder), a section for cutting (grinder), a section for washing and purification, and a section for re-melting and palletizing. The greenhouse gases and other air emissions from virgin plastic process and recycled plastic process are shown in Figure 2. It was found out that recycling of plastic from municipal solid waste is only environmentally sound if it is separated from its' generic plastic types, which makes it possible to produce a recycled plastic with properties comparable to virgin plastic [6].

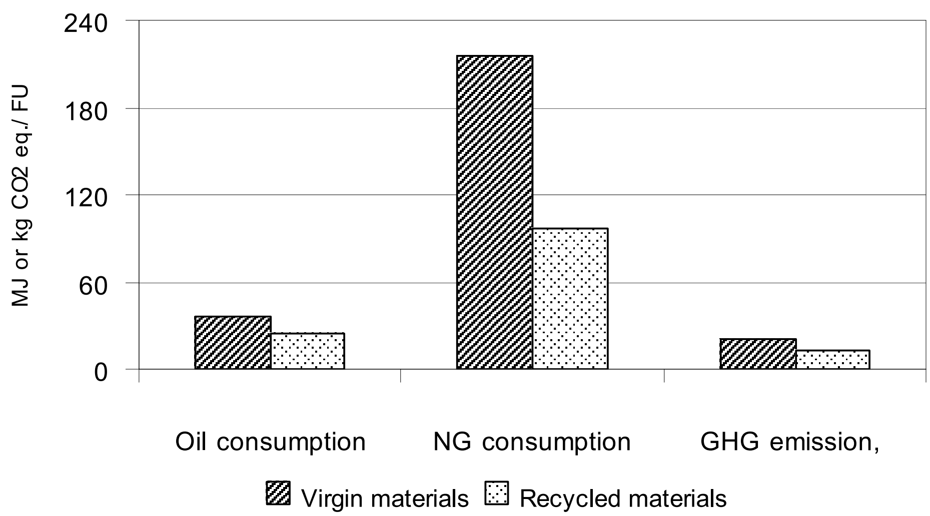
Figure 2 Greenhouse gases and other air emissions from Virgin plastic process and recycled plastic process



*Note: * Unit is ton pollutant /ton plastic*

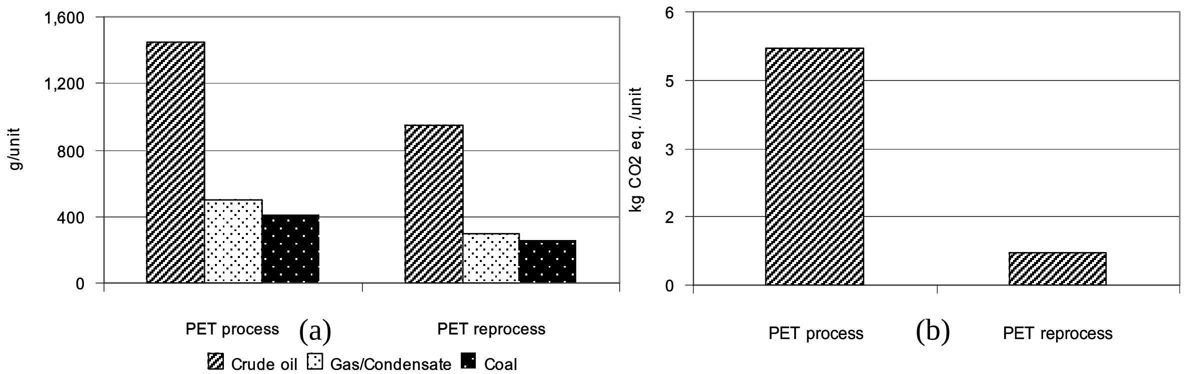
Ross S. and D. Evans (2003) investigated whether a recycle and reuse strategy for a plastic-based packaging system would substantially reduce also its overall environmental burden. The functional unit for this comparison was the packaging assembly for a 500 liter capacity refrigerator. This study compared the environmental performance of two plastic-based packaging systems, including (1) virgin material inputs, comprises moulded expanded polystyrene (EPS) components encased in a polyethylene (PE) heat-shrink wrap, and (2) recycling and reuse of materials, comprises moulded EPS components fused to a high-impact polystyrene (HIPS) coating sheet and encased in a PE heat-shrink wrap. Environmental burdens over the life-cycle of EPS/PE and EPS-HIPS/PE packaging is shown in Figure 3. Results showed that the oil consumption was lower for the EPS-HIPS/PE shrink-wrap packaging (recycled packaging) than for the EPS/PE packaging (virgin packaging). But the figure showed that for both assemblies it was quite small, being around 10% of the total energy consumption. This reinforces our earlier finding that the consumption of energy during transportation is not a major factor across the life-cycle of either packaging. Natural gas consumption is significantly less for the recycled packaging system because recycling avoids materials processing steps high in gas usage. The GHG emissions of the virgin package are more than 50% higher than for the recycled packaging. This is largely because of the reduced weight of the new package and the avoidance, by recycling, of some highly energy intensive processing steps [7].

Figure 3 Comparison of environmental burdens over the life-cycle of EPS/PE and EPS-HIPS/PE packaging for 500 L refrigerators



Arena U., *et. al.* (2003) studied life cycle energy used and GHG emissions of a plastic packaging recycling system. The object of the study was the Italian system of plastic packaging waste recycling, which was active in 2001. It collected and mechanically recycled the post-consumer PE and PET liquid containers. The phases of collection, compaction, sorting, reprocessing and refuse disposal were individually analyzed and quantified in terms of energy and material consumptions as well as of emissions in the environment as shown in Figure 4. The results indicated that the production of recycled PET requires a total amount of gross energy and GHG emissions less than what the virgin PET requires, depending on whether the process wastes (mainly coming from sorting and reprocessing activities) were sent or not to the energy recovery [8].

Figure 4 (a) Resource Consumption and (b) GHG Emissions Related to Each Selected Plastic Waste Management.

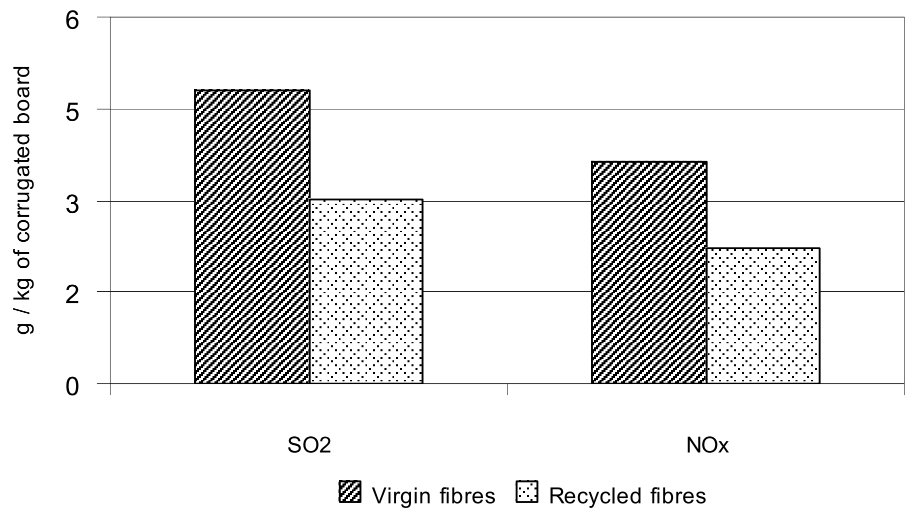


Note: All the data refer to the production of 1 kg of (recycled or virgin) PET flakes and 0.39 kg of (recycled or virgin) PE flakes

For paper recycling. Recycled paper has been typically used as a raw material in newspapers, tissues and core and packing boards. However, these traditional recovery methods as well as the utilization of wood-based construction waste have been intentionally left out of this study as the focus was on finding new concepts for the recovery of paper [5]. Previous studies have reported that the benefit of paper recycling as the following:

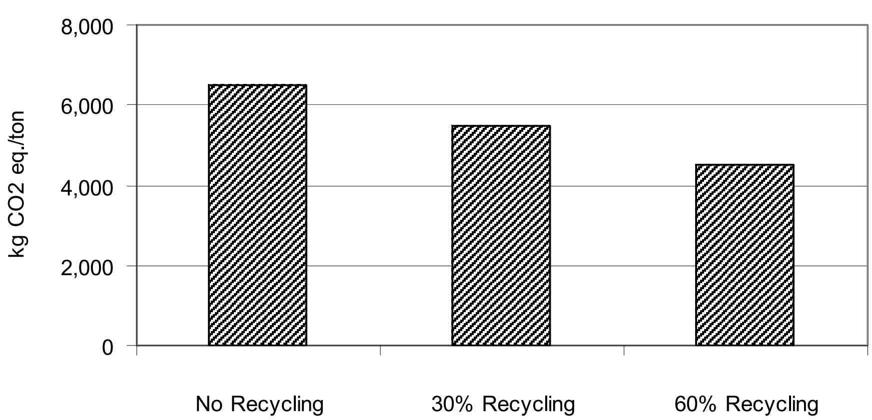
Ekvall T. (1999) demonstrated the potential importance of key methodological aspects in a Life Cycle Inventory (LCI) which is carried out to support decisions regarding waste management options for paper, board and pulp products, or regarding the choice between primary and secondary fibres as raw material in these products. Air emissions of primary and secondary fibres for corrugated board production are shown in Figure 5. It showed that the emissions from the life cycle of the corrugated board of recycled fibres were less than those of virgin fibres due to the avoided emissions from the production of material replaced by fibres from recycled cartons [9].

Figure 5 Air emissions of virgin fibres and recycled fibres for corrugated board



Pickin J., *et. al.* (2002) provided a comprehensive investigation of total GHG emission from the paper cycle in Australia, from forest through to landfill. He also assessed the effectiveness of various waste management options to reduce GHG emission from paper. Recycling is also beneficial, and is of particular interest from a management perspective because it can be controlled by the pulp and paper industry. This analysis modeled GHG emissions from the lifecycle of a ton of paper under a range of conditions for recycling (no recycling, 30% recycling and 60% recycling). Figure 6 demonstrates the effect of paper recycling at different rates. Results found that GHG emissions were reduced from 6.5 t of CO_2 equivalent per ton of paper with no recycling to 4.4 t with 60% recycling [10].

Figure 6 Total life cycle GHG emissions at different paper recycling rates.

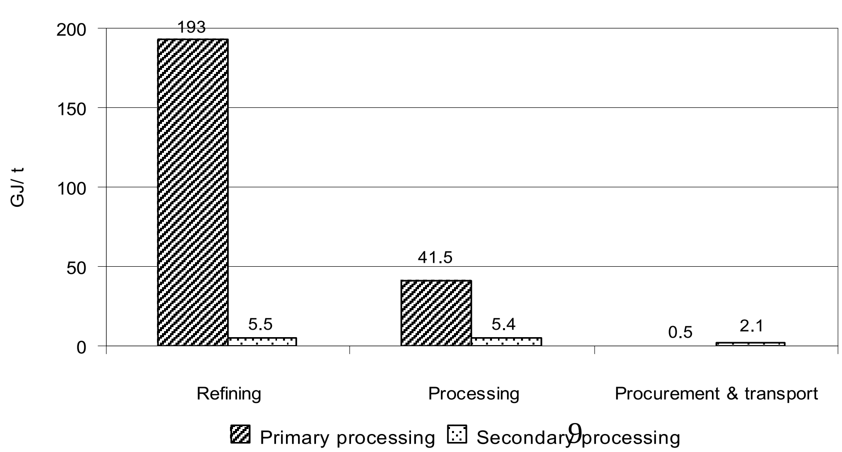


For metal recycling. Metal recycling has a long history. Scrap metal is a valuable raw material and its quality does not degrade during recycling. Nearly 98 % of the cans belonging to the deposit and refund system are recycled, but only about half of the metal packaging is recycled. Recycling of metal waste can reduce the environmental impacts from the mining industry, the space needed at landfill and the emissions originating from landfill sites. A lot of energy can also be saved by recycling metals compared with the use of virgin metals. The energy saving in steel- and sheet tin packaging manufacture is 75 % and in aluminium packaging it is 95 % [5]. Some of the previous studies on the benefit of metal recycling are the following:

W. Lea (1996) studied energy saving of recycled aluminum compared to primary aluminum. The focus of this study was to address these assumptions and to determine the degree of energy saving achieved through recycling. Comparison of unit energies for primary and secondary processing of aluminum is shown in Figure 7. The result showed that secondary aluminum had higher avoided energy value because it required much less energy to recycle than to newly produce from virgin material [11].

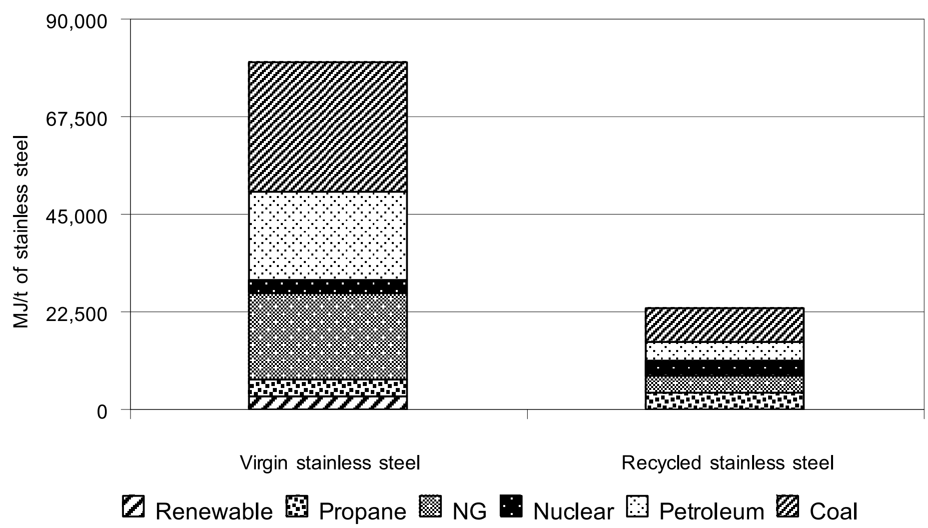
Gatti B., *et al.* (2008) studied the influence of aluminum recycling rate on the LCI of aluminum beverage cans in Brazil. The recycling rate of 36% (by weight) corresponded to the percentage of aluminum recycled from the domestic consumption of primary aluminum in 2004, while 89% (by weight) represented the rate of aluminum cans recycled from the total amount of cans produced in Brazil in 2003. Results showed that the recycling balance was always positive due to the importance of the stages that preceded the packaging production and the problem of increasing the municipal waste volume. The advantages of the recycling are obviously concentrated on the parameters related to the primary aluminum production and to the package disposal. The verified benefits of the recycling increase with the recycling rate enhancement [12].

Figure 7 Comparison of unit energies for primary and secondary processing of Al



Johnsona J., *et al.* (2008) studied the energy use to produce 1 ton of austenitic (i.e., nickel-containing) stainless-steel slab under two scenarios: (1) ‘‘Maximum Recycling’’ scenario: calculates the energy used if demand is completely met from recycled material, and (2) the ‘‘Virgin Production’’ scenario: examines stainless-steel production in the absence of scrap. Energy required to produce 1 ton of austenitic stainless steel throughout its entire life cycle is shown in Figure 8. The results showed that approximately 22,500 MJ/ton for recycled stainless steel, and 80,000 MJ/ton for virgin production. By comparing these results to the virgin production scenario, it was determined that the recycling of austenitic stainless steel required 33% of primary energy. If complete recycling of stainless steel is to occur (maximum recycling), which is not currently possible due to scrap availability, global energy use would be 67% less than the virgin production [13].

Figure 8 Energy required to produce austenitic stainless steel throughout life cycle



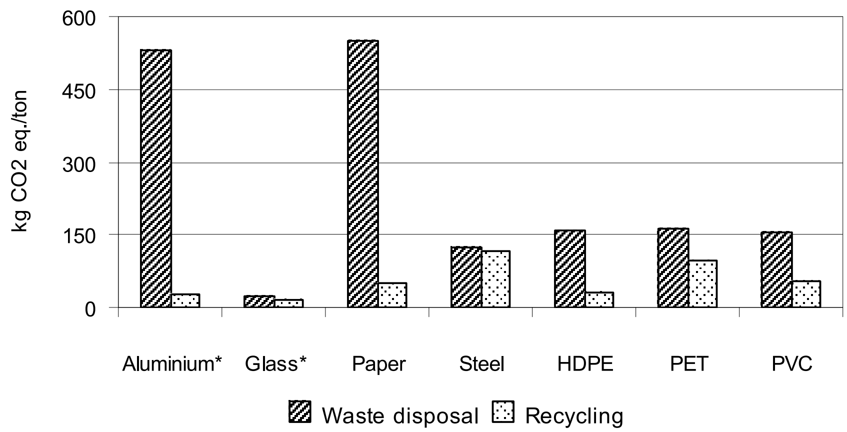
For glass recycling. The main raw materials of virgin glass are sand, soda, and lime in which all are melted into glass at 1500 degree C. Virgin glass is still widely used however it is increasingly being replaced by recovered glass. Almost all of the glass bottles belonging to the deposit system are recycled and end up being either refilled or crushed for reprocessing. There are many advantages of glass recycling. Glass can be recycled and used over and over without impairing the quality. Therefore natural resources and expensive raw materials are saved. The use of recycled glass also saves energy because it is easier to melt than the virgin raw materials [5]. Some of the previous studies conducted about the benefits of glass recycling are the following:

Vellini M.and M. Savioli. (2008) applied this methodology to a particularly energy-intensive production process, i.e. glass production for the manufacture of drink containers, in order to carry out a thorough environmental and energy analysis of the recycled and reused glass containers. The production of glass containers was compared to the production of polyethylene terephthalate (PET) containers to determine the optimal percentage of glass recycling for the minimization of energy consumption and pollutant emissions. Two cases were studied: Case 1 glass production and usage with 25% reuse and 60% recycle; and Case 2 glass production and usage with 80% reuse and 16% recycle. Based on the results, it clearly showed that the benefits of recycling were unquestionably good. It helped not only on the general improvement of the energy and technological processes but also it caused substantial reduction of the environmental impacts (with the exception of the carbon monoxide emissions which was not changed due to the increase of transport operation), which were even more valuable for those products that cannot be contained in PET bottles, such as wines and other alcoholic beverages. [14].

Some of other previous studies on the benefits of material recycling are the following:

Amelia L., *et al.* (1996) studied and compared the relative environmental impacts of a recycling system (incorporating the curbside collection of recyclable materials and their subsequent use by manufacturers), with a waste disposal system (in which the waste is disposed to landfill and primary raw materials are used in manufacture), using the LCA. GHG emissions of waste disposal and material recycling are shown in Figure 9. The result showed that the waste disposal systems generally made a larger contribution to global warming than the recycling systems. For aluminum, the recovery and use of secondary aluminum contributed to a saving of 95%, which was the largest for all materials, both in absolute and percentage terms. There were also large savings involved in recycling glass and paper, 44% and 91%, respectively. However, the difference is minimal for steel (5%). The savings for plastics are 80%, 40% and 66% for HDPE, PET and PVC, respectively [15].

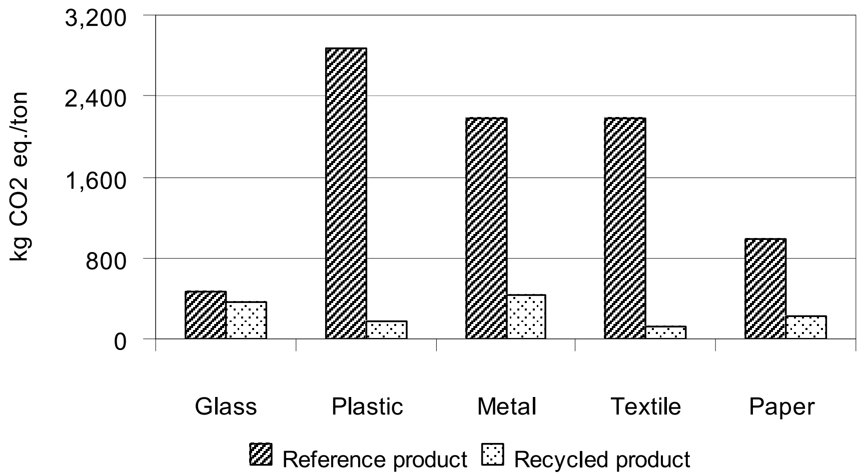
Figure 9 GHG emissions of waste disposal and materials recycling



*Note: * Unit is ton CO_2 eq./ton material*

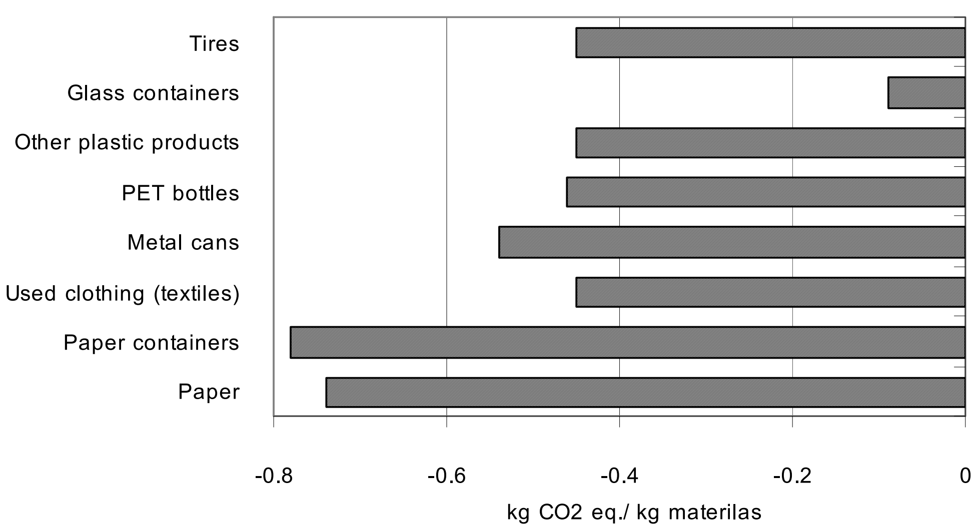
Korhonen M. and H. Dahlbo. (2007) presented the material recovery subproject and more precisely the GHG emission reduction potential results. The amount of GHG emission savings, calculated as carbon dioxide equivalent, for different waste recycling materials are presented in Figure 10. The results showed that material recycling had the potential to reduce GHG emission in all material groups. The highest potential for emission reduction existed for recycling of plastic, textile, metal, paper and glass respectively. However, the high GHG reduction potential for plastic waste recycling only existed when virgin plastics were replaced by recycled plastics. Replacing other materials produces less significant reduction [5].

Figure 10 GHG emissions of reference product and recycled product per ton of produced product.



Chen T.and C. Lin. (2008) quantified and assessed the level of GHG contribution for each type of treatment method being practiced in Taipei City's regional household waste management process. Reduction in GHG emissions from using recycled materials instead of raw materials were presented in Figure 11. Recycling created the least contribution of GHG emissions out of all waste management solutions. This is because of the usage of recycled materials instead of virgin materials in the manufacturing process. It greatly reduced not only the demand for energy but also the non-energy GHG emissions in the manufacturing process. Recycling of paper products in particular helped with forest carbon sequestration [1].

Figure 11 GHG emissions reduction from using recycled materials instead of raw materials.



DC-Environment (2008) determined the values of the main environmental indicators for each primary packaging material. This study aimed to compare the differences between the different primary package options for beer. Functional unit as defined "Beer production of 100 liter of beer and full life cycle of the packaging associated." The materials studied were PET bottles, glass long neck bottles, aluminum cans, and steel cans (all of them are 500ml beer packaging options). Results found that the production of raw materials for primary packaging production was one of the most important phases of the full LCA. A high recycling rate measurably reduced the impact on all indicators. At a recycling rate around 80% for each packaging material, aluminium cans, steel cans and PET bottles were roughly equivalent in impact reduction [16].

The benefits of materials recycling in terms of total energy use and GHG emissions as mentioned in the previous studies reviewed are summarized in Table 1. The results indicate that producing materials from recycled resources is less energy intensive and has less GHG emissions than from virgin resources. Material recycling can also decrease both the direct and indirect GHG emissions. Direct emissions are decreased when waste is neither disposed of at landfills nor treated by other methods such as combustion. Indirect emissions can be cut down by decreasing the energy consumption both in acquiring and producing raw materials and also in manufacturing the product itself [5].

3.2 Benefits of Recycling: Using Several LCA Software Programs

Manufacturing processes including recycling are often very complex and convoluted. Additionally LCA is often required input-output data intensively. LCA software program can help to structure the model scenario, display the process chains and also present and analyze the results [17]. Several commercial and public-domain LCA software programs are available. Among those are “SimaPro” from Pre’ Consultants, “GaBi” from PE International, and “JEMAI-LCA Pro” from Japan Environmental Management Association for Industry (JEMAI) which focus on the evaluation of industrial and agricultural production processes, while LCA design supporting tools such as “BEES” from National Institute of Standards and Technology (USA) and “ATHENA” from National Agency for Higher Education (Sweden) focus on the evaluation of specific building materials and components [18]. SimaPro, GaBi, and JEMAI-LCA Pro are available at National Metal and Materials Technology Center and several universities in Thailand. The databases in those three software programs include production processes of virgin and recycled materials. The details of the databases in those LCA software programs for materials recycling are summarized in Table 2.

Results of life cycle GHG emissions of plastics recycling (from recycling process), virgin plastics, and recycled plastics (including: PVC, PS, PP, PET and PE) obtained from LCA software databases are presented in Figure 12. Life cycle GHG emissions from recycling of others materials (including: glass, cardboard, paper, iron and aluminum) obtained from LCA software databases are presented in Figure 13.

As shown in Figures 12 and 13, the results demonstrated that recycling of materials has the potential to reduce GHG emissions and energy consumption. It is beneficial to substitute virgin material with recycled material because the emissions from virgin material acquisition and production can be avoided. In most cases, the replacement of virgin materials by recycled materials decreases the use of net energy and thus the GHG emissions originating from energy production and usage also decrease. GHG emissions can also be reduced by avoiding the use of virgin materials which produce emissions directly in the extraction phase. However, in some cases, the benefits of recycling are less if too much energy is required during transportation and recycling process [5].

Table 1: Overview of LCA studies for material recycling

Reference	Recycled materials	Virgin materials	Total energy[a]	GHG emissions[a]
Molgaard C. ,1995 [6]	HDPE, LDPE, PP, PS, PET, PVC	Virgin: (HDPE, LDPE, PP, PS, PET ,PVC)	-	R<V
Ross S. and D. Evans, 2003 [7]	EPS-HIPS/PE	EPS/PE	R<V	-
Umberto Arena, *et al*., 2003 [8]	PET	Virgin PET	R<V	R<V
Ekvall T., 1999 [9]	Paper	Virgin paper	-	R<V
Pickin J. ,*et al*.2002 [10]	Paper	Virgin paper	-	60%R<30%R <NR
W. Lea. 1996. [11]	Aluminium	Virgin Aluminium	R<V	-
Gatti B., *et al*.2008 [12]	Aluminium	Virgin Aluminium	89%R<36%R <NR	89%R<36%R <NR
Johnsona J., *et al*.2008 [13]	Stainless steel	Stainless steel	R<V	-
Vellini M. and M. Savioli. 2008 [14]	Glass (R1 and R2)[b]	Virgin glass Virgin PET	R2<PET <R1<V	R2<PET<R1<V
Amelia L., *et al*.1996 [15]	Glass, Paper, Steel, HDPE, PET, PVC	Virgin: (Glass, Paper, Steel, HDPE, PET, PVC)	-	R<V
Korhonen M. and H. Dahlbo.2007 [5]	Glass, Plastic, Metal, Textile, Paper	Virgin : (Glass, Plastic, Metal, Textile, Paper)	-	R<V
Chen T.and C. Lin.2008 [1]	Paper, Metal , Plastic, Glass, Tires, Metal	Virgin: (Paper, Metal , Plastic, Glass, Tires, Metal)	-	R<V
DC-Environment, 2008 [16]	Paper, Aluminium , Steel, Glass	Virgin: (Paper, Steel, Aluminium , Glass)	-	R<V

Note: [a] R = Recycled materials, V = Virgin materials, NR = No recycled
[b] R1: glass production and usage with 25% reuse and 60% recycle
R2: glass production and usage with 80% reuse and 16% recycle

Table 2: Databases of materials recycling in some LCA software programs

LCA software	Database	Materials recycling								
		PVC	PS	PP	PET	PE	Glass	Paper	Iron	Al
SimaPro 7.1.8	RER (Ecoinvent) [19]	✓	✓	✓	✓	✓	✓		✓	✓
	BUWAL 250 [20]	✓	✓	✓	✓		✓	✓		
	FAL (IDEMAT) [21]						✓			
JEMAI Pro [22]	Japanese database	✓	✓		✓		✓	✓		✓
GaBi 4.0 [23]	-									✓

Figure 12 Life Cycle GHG emissions from plastics recycling, virgin plastics, and recycled plastics *($GHG_{Recycled\ plastic}$ = $GHG_{Plastic\ recycling}$ - $GHG_{Virgin\ plastic}$)*

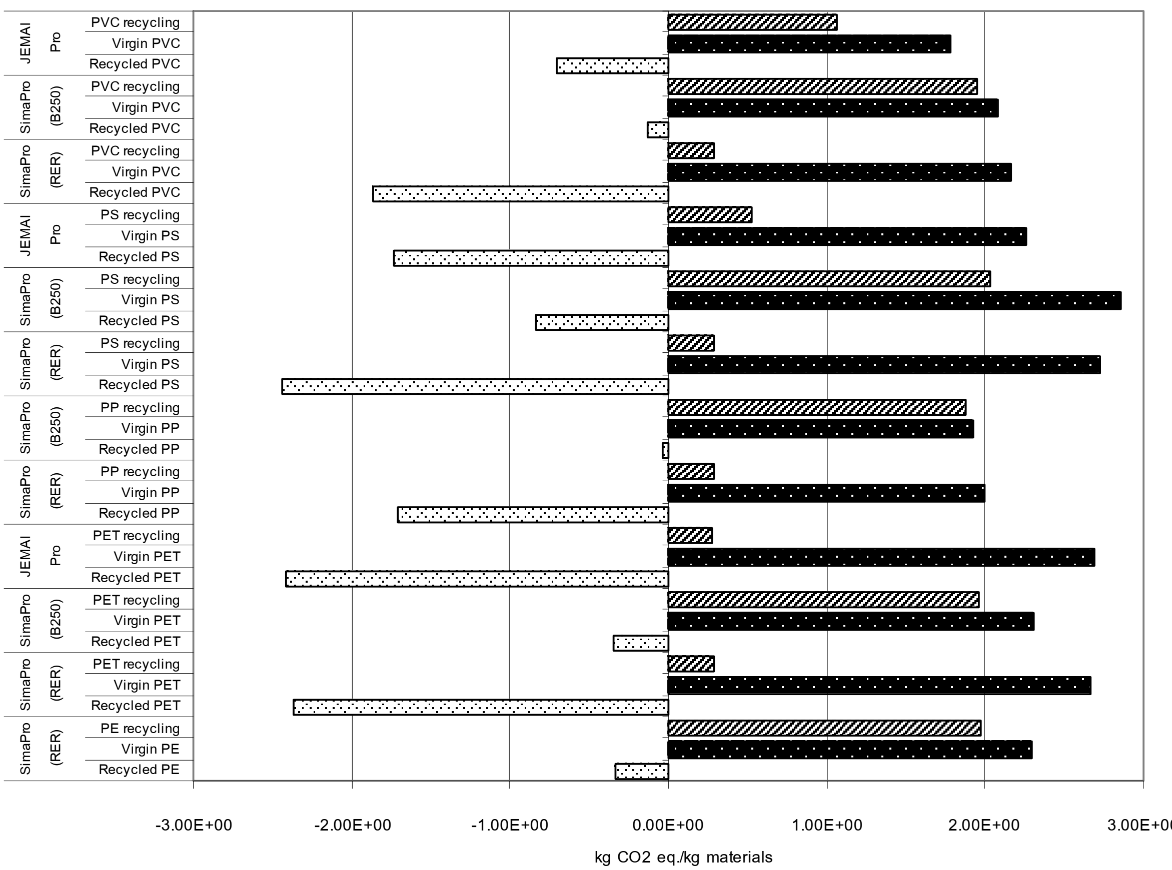
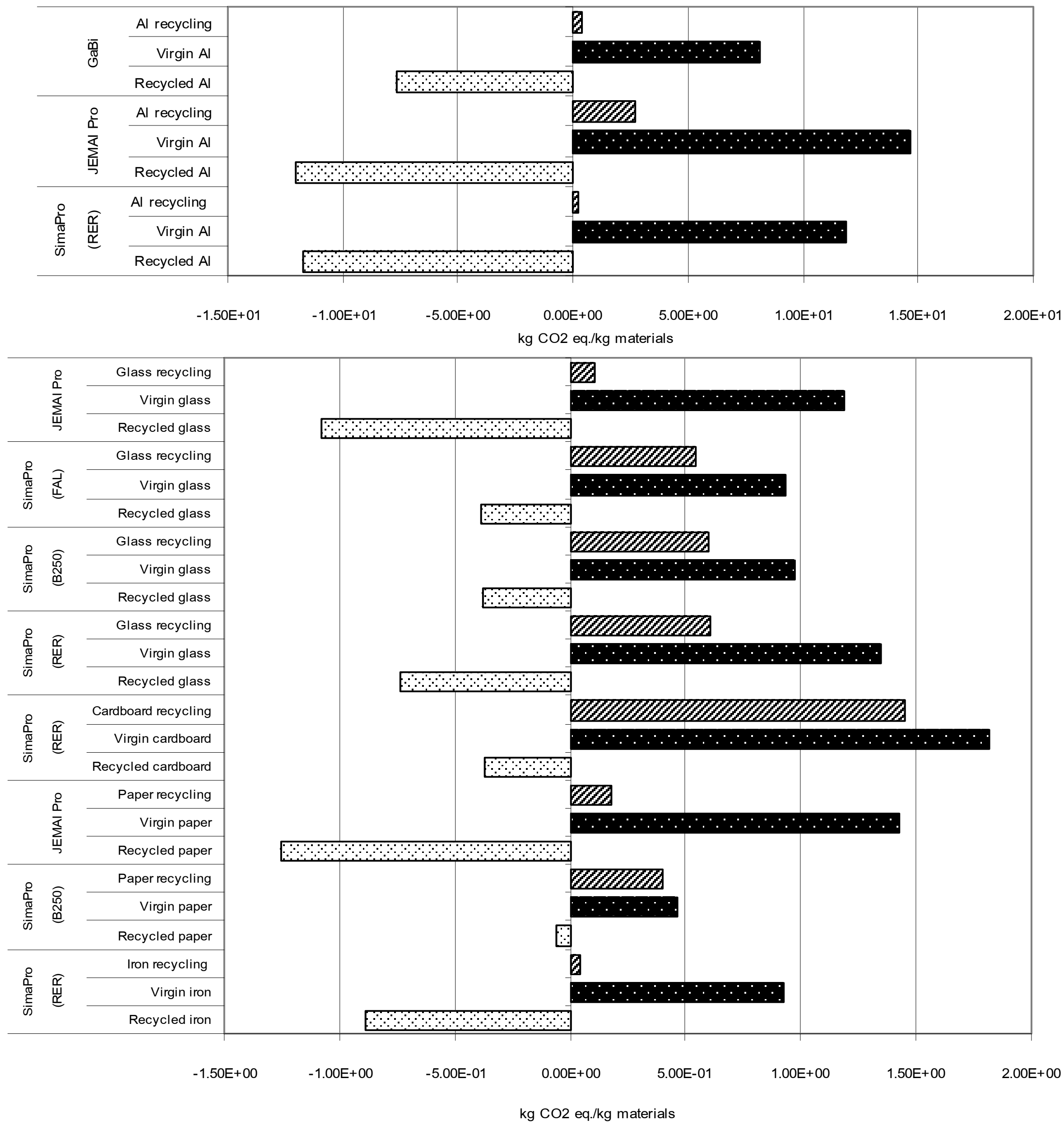


Figure 13 Life Cycle GHG emissions from materials recycling, virgin materials and recycled materials *(GHG$_{Recycled\ material}$ = GHG$_{Material\ recycling}$ - GHG$_{Virgin\ material}$)*



4. Conclusion

The 3R measures especially resource recycling of various materials are presented in this study. These can contribute greatly to the eco-image of waste management. The quantitative comparison using LCA study between each scenario shows that the recycling option is always environmentally preferable. Material recycling has the potential to reduce greenhouse gas emission, energy consumption, and other environmental impacts throughout the whole life cycle in all material groups. Due to the substitution of virgin materials with recycled materials, the emissions from extraction and manufacturing of products from virgin materials can be avoided. GHG emissions for the whole life cycle from raw materials extraction, materials processing, products manufacturing, usage, and disposal including transportation (cradle-to-grave approach) can be reduced in situations where the waste materials and/or waste products are recycled instead of being combusted, treated or disposed of at disposal sites. The results of the study clearly show that 3R measures including resource recycling have a net gain on environmental benefits and perform better than the end-of-pipe treatment methods such as landfill and incineration in terms of life cycle reduction of greenhouse gas emission, energy consumption, and other environmental impacts.

Reference

Chen T. and C. Lin. 2008. "Greenhouse gases emissions from waste management practices using Life Cycle Inventory model", *Journal of Hazardous Materials,* 155 (2008) 23–31.

Spire Research and Consulting Pte Ltd. 2006. *Recycling for the Next Generation, How impending recycling legislation will change the way businesses work.*

Apisitpuvakul W., et al. 2008. "LCA of spent fluorescent lamps in Thailand at various rates of recycling", *Journal of Cleaner Production, 16 (2008) 1046-1061.*

Curran M.A. 1997. *Environmental Life Cycle Assessment*. New York: McGraw-Hill.

Korhonen M. and H. Dahlbo. 2007. *Reducing Greenhouse Gas Emissions by Recycling Plastics and Textiles into Products.* The Finnish Environment 30/2007.

Molgaard C. 1995. "Environmental impacts by disposal of plastic from municipal solid waste", *Resources Conservation and Recycling, 15 (1995) 5l-63.*

Ross S. and D. Evans, 2003. "The environmental effect of reusing and recycling a plastic-based packaging system", *Journal of Cleaner Production, 11 (2003) 561–571.*

Arena U., et al. 2003. "Life cycle assessment of a plastic packaging recycling system". *Int J LCA 8 (2003) 92–98.*

Ekvall T. 1999. "Key methodological issues for life cycle inventory analysis of paper Recycling", *Journal of Cleaner Production, 7 (1999) 281–294.*

Pickin J., et al. 2002. "Waste management options to reduce greenhouse gas emissions from paper in Australia", *Atmospheric Environment, 36 (2002) 741–752.*

Lea W. 1996. "Plastic incineration versus recycling: a comparison of energy and landfill cost savings", *Journal of Hazardous Materials, 47 (1996) 296-302*.

Gatti B., et al. 2008. "Recycling of aluminum can in terms of Life Cycle Inventory (LCI)", *Int J LCA, 13 (2008) 219 –225.*

Johnsona J., et al. 2008. "The energy benefit of stainless steel recycling", *Energy Policy, 36 (2008) 181–192.*

Vellini M. and M. Savioli. 2008. "Energy and environmental analysis of glass container production and recycling", *Energy (2008) 1–7.*

Amelia L., et al. 1996. "Life cycle assessment and economic evaluation of recycling: a case study", *Resources Conservation and Recycling, 17 (1996) 75-96.*

DC-Environment. 2008. *Life Cycle Assessment of four beer packaging options: glass bottle, PET bottle, aluminium can & steel can*.

Unger N., et al. 2000. *General requirements for LCA software tools*. Institute of Waste Management, BOKU – University of Natural Resources and Applied Life Sciences, Vienna, Austria.

Fujimoto S., et al. 2000. *Evaluation of recycling technologies of concrete related materials: To ward reduction of waste and CO_2 emission*. JSPS Research Fellow, Graduate School of Engineering, Department of Architecture, University of Tokyo.

Ecoinvent. 2003. "*Final Report Eco-invent 2000*", SimaPro 7.0, Amersfoort.

BUWAL 250. 1996. *Okoinventare fur Verpackungen*. Schriftenreihe Umwelt, Bern.

Franklin Association. 1998. *Franklin USA 98 database*. Source: www.fal.com

Japan Environmental Management Association for Industry. 2002. *Japan life cycle inventory database.*

PE Europe GMBH. 2003, *GaBi 4.0 manual*.