Australian Journal of Basic and Applied Sciences, 4(9): 4313-4322, 2010
ISSN 1991-8178

Life Cycle Impact Assessment (LCIA) Using TRACI Methodology: an Analysis of Potential Impact on Potable Water Production

[1]Amir Hamzah Sharaai, [2]Noor Zalina Mahmood and [2]Abdul Halim Sulaiman

[1]Institute of Teacher Education, Tuanku Bainun Campus, 14000 Bukit Mertajam, Penang
[2]Institute of Biological Sciences, Faculty of Science, University of Malaya, 50603 Kuala Lumpur

Abstract: Life cycle assessment (LCA) is a method to analyse a particular product or service. It begins with the process of extraction until the product is exhausted by 'cradle-to-grave' analysis. The LCA includes establishment of an inventory, that is all types of emissions and also waste products. After that, this inventory would be translated or transformed to show the impact on environment in the life cycle impact assessment (LCIA). Two LCIA methods has been accepted such as Midpoint and Endpoint approach. TRACI is one method that uses Midpoint approach. From the analysis on the two stages of potable water production, that is between construction stage and production stage, production stage contributes a higher impact in comparison to the construction stage. At the production stage, the weakness was due to the usage of PAC, lime and electricity. However, at the construction stage, the process of producing steel seems to be the main source of impact such as HH cancer and HH noncancer. The process of producing PAC liberates Nitrogen oxides and Sulfur oxides which contributes to five types of impacts such as acidification, HH criteria air – point, HH criteria air – mobile, euthrophication and smog. In lime production, four impacts are HH cancer ground - surface, HH cancer root – zone, HH noncancer ground – surface and HH noncancer root –zone) results from the emissions during the waste treatment (drilling waste to land farming) such as Arsenic and Aluminum. Whereas in the production of electricity, four very high impacts give rise to global warming, HH cancer, HH noncancer dan ecotoxicity. Even though the impact from construction stage is very low in comparison to the production stage, a few problems have been detected during the process of producing building materials. Among those materials, the production of steel produces the highest impact to the environment.

Key words: TRACI method, LCIA, potable water production, Midpoint approach, Polyaluminium chloride (PAC) and steel production

INTRODUCTION

Impact assessment is used to identify significant potential environmental effect by using the results of life cycle impact analysis (LCI). LCIA is very different from other techniques such as environment impact assessment (EIA) and risk assessment because the approach uses functional unit. LCIA comprises four elements namely the classification, characterization, normalization and weighting but normalization and weighting are the optional element (Koroneos, Dompros, Roumbas, & Moussiopoulos, 2005). According to Jolliet, Brent, (2003), the classification of LCI due to the impact categories is through the impact pathway which begins from LCI results until the end-point. The impact pathway is explained in ISO (Jolliet, Brent *et al.*, 2003) where:

> 'LCI results are classified into the impact categories and category indicators that can be stated in any LCI results (mid) with the end-point category'.

In accordance with the above explanation, two approaches are developed to explain the inter-connection of the LCI results with the environmental impacts via mid-points or end-points approaches (Heijungs et al., 2003; Jolliet, Margni et al., 2003; Jolliet et al., 2004; Ortiz, Francesc, & Sonnemann, 2009; Sleeswijk, van Oersc, Guinée, Struijsd, & Huijbregtsb, 2008; Soares, Toffoletto, & Deschenes, 2006). According to Bare, Hofstetter, Pennington, & Udo de Haes, (2000), the main difference between both models is the methodology how category indicators are presented to translate the achieved impact categories.

Corresponding Author: Amir Hamzah Sharaai, Institute of Teacher Education, Tuanku Bainun Campus, 14000 Bukit Mertajam, Penang
E-mail: amirhamzah5@yahoo.com

Figure 1 explains the impact pathway beginning from LCI results until the end-point. The emission of ozone depletion gasses is used as an example for the characterization of ozone depletion gasses that can be conducted either until mid-point or end-point. Mid-point impact is the ozone layer depletion. Impacts are human health, natural biotic environment and manmade environment.

A) Midpoint Approach:

The LCIA mid-point approach also known as problem-oriented approach (Dreyer, Niemann, & Hauschild, 2003; Ortiz et al., 2009) or classical impact assessment method (Jolliet, Brent et al., 2003; Jolliet et al., 2004). The term mid-point refers ti the category indicator for each impact category which is expressed in the mid pathway of impact between LCI results and end-point (Josa, Aguado, Cardim, & Byars, 2007). Mid-point translates the category impact into real phenomenon as shown in Figure 1. Impacts that are in the mid-point are climate change, acidification and aquatic toxicity (Sleeswijk et al., 2008). Some methodologies developed using the midpoint approach is CML 2001 (Dreyer et al., 2003; Heijungs et al., 2003), EDIP 97 and TRACI (Jolliet et al., 2004).

B) Endpoint Approach:

The end-point LCIA methodology is also known as damage-oriented approach (Dreyer et al., 2003). End-point approach according to Heijungs *et al*., (2003) are the elements inside the impact pathway that consists of independent value for society. The term 'end-point' is refers to the category indicator for each impact category located at the end of impact pathway as in the **Figure 1**. End-point indicator translates the category impact based on the area of protection such as human health, natural environmental quality, natural resources and human made environment (Bare & Gloria, 2008). Example of end-point methodology are Eco-indicator 95 and 99, EPS 92, 96 and 2000 and LIME 2003 (Pennington et al., 2004).

According to Reap et al. (2008), there are several factors affecting the level of confidence and suitability of LCA research result which include option of LCIA methodology either using the mid-point or end-point approach. Reap et al. (2008) mentioned, end-point impact category is less comprehensive and posses higher level of uncertainty compared to mid-point impact category. Nevertheless mid-point impact category is difficult to be interpreted especially in the process of decision making because the mid-point impact category is not directly correlated with the area of protection (i.e. damage to human health, ecosystem quality and resource depletion) which is practiced by the end-point.

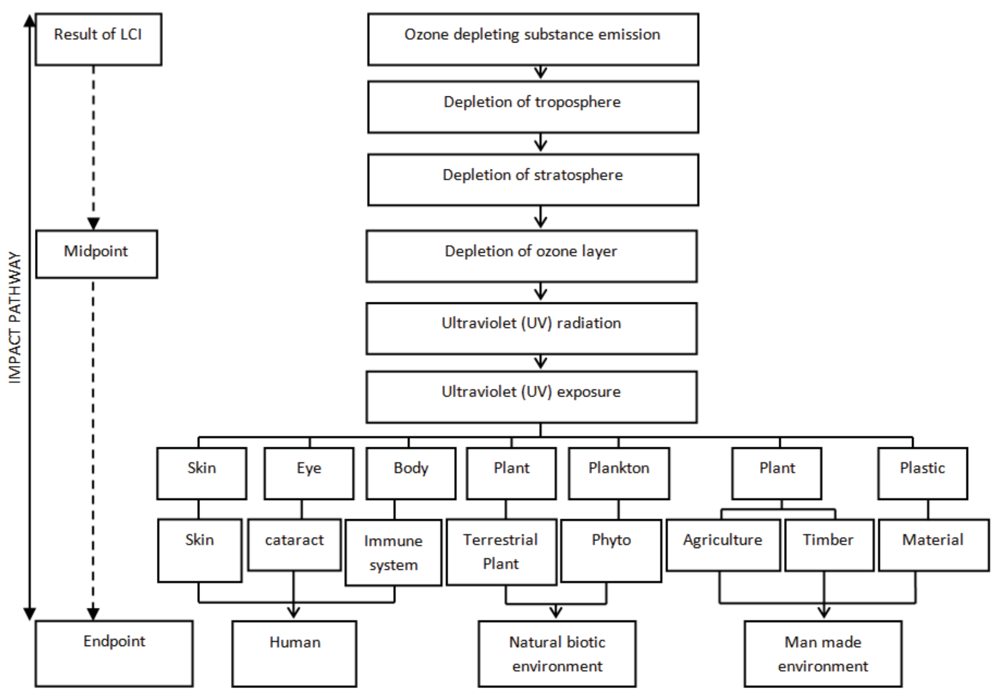

Fig. 5-12: Impact pathway connecting the emission to several deterioration categories

2.0 Methodology of LCA:

There are four main phases in LCA as suggested in ISO 14040 series:

2.1 Goal and scope definition (ISO 14040)
2.2 Life cycle inventory (LCI) (ISO 14041)
2.3 Life cycle impact assessment (LCIA) (ISO 14042)
2.4 Life cycle assessment and interpretation (LCAI) (ISO 14043)

2.1 Goal and Scope Definition:

In goal definition and scoping, the use of the results is identified, the scope of the study is stated, the functional unit is defined, and a strategy and procedures for data collection and data quality assurance are established.

2.1.1 Objectives:

The objective of this research is to get a clear picture of impact potential produced by potable water production where two phases were involved namely production stage and construction stage using LCIA method that is TRACI method. This research will identify which significant impact by comparing them using normalization and weighting procedures so that suggestions to reduce the impact can be made.

2.1.2 Functional Unit:

Functional unit is quantified performance of a product system for use as a reference unit in a life cycle assessment study (ISO14000, 2000). A constant value must be created to make the comparison (Miettinen & Hamalainen, 1997). Functional unit for this study is the production of $1m^3$ of treated water a day that fits the standard quality set by Ministry of Health, Malaysia.

2.1.3 Description of the System under Study:

There are two stages which became the basis of comparison for this study namely production construction stage.

Production Stage:

Raw water extracted from rivers will go through the following process in the water treatment plant (Sastry, 1996):

- **Screening**, to remove floating big sized rubbish on the surface of the water.
- **Coagulation and flocculation**, coagulation process is a process of forming particles called floc. Coagulant need to be added to form floc. The coagulants that are normally use includes Aluminium Sulphate, Ferric Sulphate and Ferric Chloride. Tiny flocs will in turn attract each other while at the same time pulling the dissolved organic material and particulate to combine, forming a big flocculant particle. This process is called flocculation.
- **Settling**, Aggregated flocs settle on the base of the settler. The accumulation of floc settlement is called settling sludge.
- **Filtration**, part of the suspended matter that did not settle goes through filtration. Water passing through filtration consisting of sand layers and activated carbon or anthracite coal.
- **Disinfection** process is needed to eliminate the pathogen organisms that remain after filtration. Among the chemicals used for the disinfection are chlorine, chloramines, chlorine dioxide, ozone, and UV radiation.

b. Construction Stage:

Main building materials used for water treatment plant building are concrete and steel. Concrete is a type of composite material which is usually used in construction. It is a combination of the following:

a) Cement
b) Fine aggregate / sand
c) Coarse aggregate
d) Water

The quality of the concrete used depends on the quality of the raw materials in coarse aggregate and water, rate of mixing, the method of mixing, transportation and compression methods. If the raw materials used are not of good quality, the concrete produced will have low quality and causes the concrete to be weak and does not fulfill the fixed specifications. So, concrete technology warrants that all the materials that will be used should be tested first and certified through fixed standardizations. before being used in construction works.

Steel increases the tensile strength of the concrete structure. Reinforcement steel functions to increase the tensility strength of the concrete structure. Types of reinforcement steel that are used are as follows:-

1. Mild steel reinforcement /*mild steel*
2. Reinforcement steel with high tensility
3. Fabric steel (*fabric*)

The steel that are provided are 12m long, with diameter of 6mm, 8mm, 10mm, 12mm, 16mm, 20mm, 22mm, 25mm dan 32mm. The reinforcement steel will be cut and moulded according to the concrete structure design. Reinforcement steel with high tensility is used as the backbone concrete structure because it has high strength. Mild steel reinforcement are usually in fixation for reinforcement steel with high tensility where high tensility is not needed. High tension where high force not needed. Fabric steel (*fabric*) is used in a wide concrete surface area such as floor. Comes in sizes of 2.4m x 1.8m with steel diameter 4mm to 12mm. Distance between each steel rods are different based on types of fabric. Reinforcement steel that is used should be free from any dirt and rust, so that it is protected from water and humidity.

2.2 Life Cycle Inventory (LCI):

The inventory of the studied LCA system includes information on the input and output (environmental exchanges) for all the process within the boundaries of the product system (see **Figure 2**). The inventory is a long list of material and energy requirements, products and co-products as well as wastes. This list is referred to as the material and energy balance, the inventory table, or the eco-balance of the product (Guinée, 2002). This LCA study is a streamlined LCA where background data for electricity, chemicals and transport using database contained in the Jemaipro and Simapro 7 software. Foreground data collected from the treatment plant are: (see **table 1**)

- Electricity usage, and
- Chemicals for water treatment such as Aluminium sulphate (alum), Polyaluminium chloride (PAC), Chlorine, and Calcium hydroxide (lime)
- Building material such as steel, gravel, sand and cement

Filtration material (activated carbon and anthracite) and coagulant (ferrochloride) are not included in this study because all the water treatment plants in Malaysia are not using all these materials.

Background data for all building materials and chemicals was obtained from Japan Environmental Management Association for Industry (JEMAI) – Polyaluminium chloride (PAC), BUWAL 250 - chlorine, alum, and Electricity, ETH-ESU 98 - lime, LCA Food DK - tap water, and IDEMAT 2001 - cement, steel, sand and gravel.

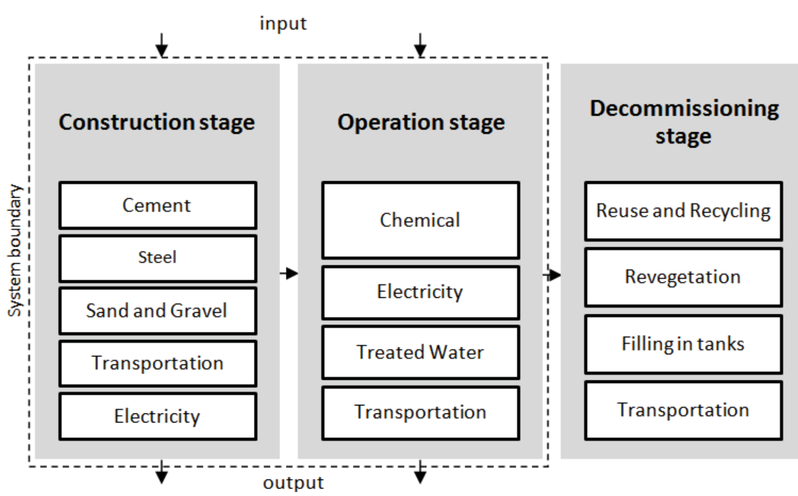

Fig. 2: System Boundary of Potable Water Treatment Plant

Table 1: Foreground data for construction stage and production stage.

Construction Stage		Production Stage	
Steel (kg)	8.78	Alum (kg)	22.55
Cement (kg)	30.72	Chlorine (kg)	3.65
Gravel (kg)	70.72	Polyaluminium chloride (PAC) (kg)	16.85
Sand (kg)	47.15	Lime (kg)	11.12
Electricity (kwh)	0.09	Electricity (kwh)	397.28
Tap water (liter)	477.26		

2.3 Life Cycle Impact Assessment (LCIA):

TRACI is a short form of The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts. TRACI was developed by United States Environmental Protection Agency (US EPA) to facilitate the characterization of environmental stressor which have potential in resulting impacts such as global warming, euthrophication, ozone depletion, tropospheric ozone (smog formation), ecotoxicity, human health noncancerous effects, fossil fuel depletion and human health criteria-related effects. The objective of TRACI's method is specifically for conducting LCA and also proposed for wider uses like pollution prevention and sustainability metrics.

TRACI's development has gone through several steps such as selection of impact categories, evaluation of existing methods and categories that need to give priority for further research. This method is using the mid-points approach. Study on impact category such as smog formation, acidification, human health (HH) cancer, euthrophication, human health (HH) criteria pollutants, and human health (HH) non cancer aimed to describe the potential effects in United States. Nevertheless, the probabilistic analyses at the spatial resolution and determination of an appropriate level for sophistication are needed for every impact model because this method is designed to be suitable for current variation (Bare, Norris, Pennington, & McKone, 2003).

Generally there are 3 steps in LCIA:

2.3.1 Classification and Characterization
2.3.2 Normalization, and
2.3.3 Weighting

Arguing that normalization and weighting is still very much under debate and because of possible misinterpretation and misuses, the authors of TRACI determined that the state of the art for the normalization and weighting processes did not yet support inclusion in TRACI.

2.3.1 Classification and Characterization:

Classification is an inventory collection process from life cycle to several impact categories (Moberg, Finnveden, Johansson, & Lind, 2005), while characterization according to Bovea & Gallardo, (2006), is a type of summation of Life Cycle Inventory for every element under same impact category. The summation of every element using characterization factor and summation value then recognized as category indicator (Ntiamoah & Afrane, 2008). In ISO 14040: (2000, 2005), category indicator of Life Cycle impact category indicator can be defined as a value that indicates each impact category. Curran (2006) suggested that the equation for category indicator is as below and the relationship between impact categories and characterization factor.

Inventory Data x Characterization Factor = Category Indicator

2.3.1.1 Characterization for Construction Stage:

From the 14 impact shown in **Figure 3**, 10 impacts were dominated by the process of steel production. The rest is from tap water production. Impacts contributed by steel production are smog (95.8%), ecotoxicity (80%), ozone depletion (51%), euthrophication (91.9%), HH criteria air – mobile (92.8%), HH criteria air – point source (93.3%), HH noncancer (95.8%), HH cancer (99.9%), acidification (94.4%) and global warming (87.5%). **Table 4** shows the categories of impact produced by the building materials and electricity based on the units used in TRACI.

In the production of steel, a lot of emissions causes impact as mentioned above. For example, smog released in steel production accounts for 91.4% of total Nitrogen oxides liberated. Coincidentally, bulk carrier involved in steel production contributes as high as 91.4% of total Nitrogen oxides in steel production. For the ecotoxicity category, aluminium is greatly liberated due to the production of electricity. Halon 1301 released from generation of electricity is the sole contributor that lead to ozone depletion. Eutrophication is caused by the release of nitrogen oxides (79.9%) which is greatly released due to transportation that is bulk carrier. For HH criteria air – mobile and HH criteria air – point source, Sulphur dioxide is greatly released that is also due to the

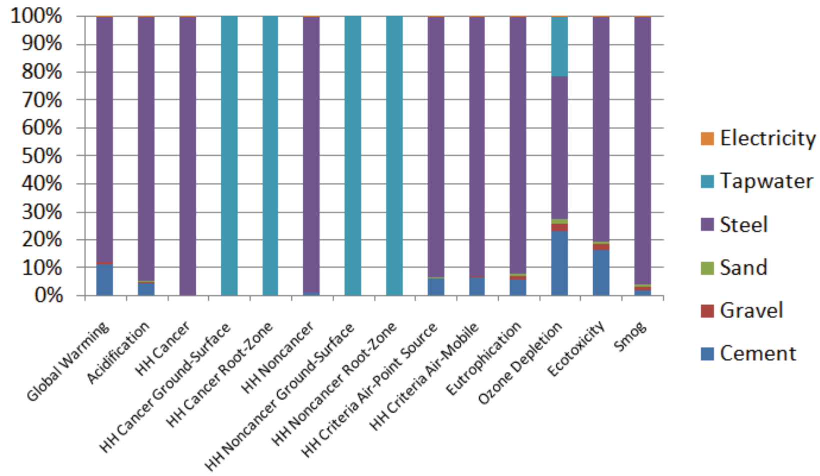

Fig. 3: Characterization to impact categories from building materials and electricity

Table 4: Characterization to impact categories from building materials and electricity

Impact category	Unit	Cement	Gravel	Sand	Steel	Tapwater	Electricity
Global Warming	CO2 eq.	11.51692	0.617202	0.411497	89.45905	0.185053	0.072824
Acidification	H+ moles eq.	2.086898	0.375575	0.250401	47.16471	0.083264	0.006585
HH Cancer	benzene eq.	0.003311	0.000383	0.000255	2.882622	0.000163	1.91E-05
HH Cancer Ground-Surface	benzene eq.	0	0	0	0	6.82E-06	0
HH Cancer Root-Zone	benzene eq.	0	0	0	0	6.82E-06	0
HH Noncancer	toluene eq.	64.66954	7.474754	4.983522	5122.262	1.297514	0.461352
HH Noncancer Ground-Surface	toluene eq.	0	0	0	0	0.01977	0
HH Noncancer Root-Zone	toluene eq.	0	0	0	0	0.045119	0
HH Criteria Air-Point Source	PM2.5 eq.	0.011233	0.000821	0.000547	0.174821	1.46E-05	5.57E-06
HH Criteria Air-Mobile	PM2.5 eq.	0.012993	0.000885	0.00059	0.186424	1.77E-05	6.73E-06
Eutrophication	N eq.	0.001533	0.000339	0.000226	0.024078	1.74E-05	7.13E-06
Ozone Depletion	CFC-11 eq.	1.48E-07	1.71E-08	1.14E-08	3.27E-07	1.37E-07	1.6E-10
Ecotoxicity	2,4-D eq.	2.309199	0.266908	0.177951	11.21533	0.026712	0.015646
Smog	NOx eq.	0.008292	0.007255	0.004837	0.475404	0.000363	0.000135

transportation specifically bulk carrier. For HH noncancer and HH cancer, both impacts are greatly caused by the release of Dioxins that is 100% from the production of steel. As for the acidification category, the main contributors are nitrogen oxides and sulphur oxides which are released in transportation (bulk carrier). For the ecotoxicity, the highest impact was given out from aluminium (38.9%) and copper (25.6%) which are produced from the generation of electricity using oil, gas and coal. The final impact caused by the process of steel production is global warming. Global warming is greatly caused by carbon dioxide (99.6%) which is released by the production of steel and also transportation.

If we observe **Table 4**, only four impacts are only caused by tap water production that is HH cancer ground – surface, HH cancer root – zone, HH noncancer ground – surface and HH noncancer root – zone. In the categories of HH cancer ground –surface and HH cancer root – zone, arsenic seems to be the main cause whereas in HH noncancer ground – surface and HH noncancer root – zone categories the main contributor is aluminium. The production of arsenic and aluminium is caused by the process of inorganic chemicals used in the production of tap water.

2.3.1.2 Characterization for Production Stage:

If we observe **Figure 4**, two types of chemicals and electricity significantly causes the highest impact such as PAC, Lime, Alum and Electricity. The process of lime production causes the highest four impacts, that is acidification, HH cancer ground – surface, HH cancer root – zone, HH noncancer ground - surface and HH noncancer root – zone. For PAC, five impacts are involved such as acidification, HH criteria air – point source, HH criteria air - mobile, euthrophication and smog. Four other impacts namely global warming, HH cancer, HH noncancer and ecotoxicity are mostly contributed by electricity production.

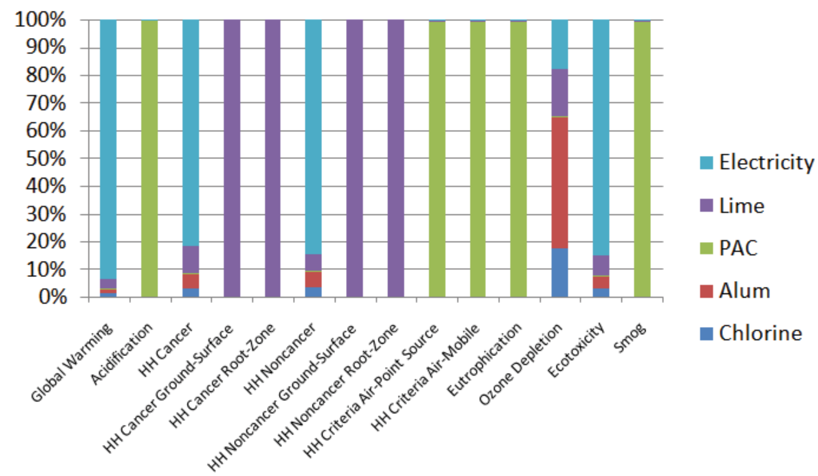

Fig. 4: Characterization to impact categories from chemicals and electricity

In the lime production, all the four impacts mentioned earlier (HH cancer ground - surface, HH cancer root – zone, HH noncancer ground – surface and HH noncancer root –zone) were caused by the emission while treating the waste (drilling waste to land farming) such as arsenic causes HH cancer ground – surface (99.7%) and also causes impact HH cancer root – zone (99.7%). Apart from that, aluminium too is released causing impacts like HH noncancer ground – surface (86.7%) and HH noncancer root – zone (88%).

In the production of PAC, the substance that has been detected contribute five impacts which is very high as mention earlier (acidification, HH criteria air – point, HH criteria air – mobile, euthrophication and smog). These impacts were solely caused by Nitrogen oxides. However, in the cas of acidification, apart from Nitrogen oxides, Sulphur oxides too is released which is about 55.9%.

Meanwhile, in the production of electricity, four very high impact contributes to global warming, HH cancer, HH noncancer and ecotoxicity. Carbon dioxide is the major contributor to global warming as the gas accounts for 94.8% of total contribution. Category HH cancer and HH noncancer also result from the release of lead into water which is about 73.9% and 98.8% respectively. For ecotoxicity, aluminium is the major contributor to this impact totaling 94.4% in comparison to other materials. The **Table 5** shows the contribution of chemicals and electricity with their respective units.

Table 5: Characterization to impact categories from chemicals and electricity

Impact category	Unit	Chlorine	Alum	PAC	Lime	Electricity
Global Warming	CO2 eq.	4.580285	6.220082	0.372246	11.64865	321.4611
Acidification	H+ moles eq.	3.280547	16.90245	13774.38	1.223967	29.06875
HH Cancer	benzene eq.	0.00329	0.005723	3.57E-05	0.010222	0.084196
HH Cancer Ground-Surface	benzene eq.	0	0	2.2E-10	6.83E-05	0
HH Cancer Root-Zone	benzene eq.	0	0	2.2E-10	6.83E-05	0
HH Noncancer	toluene eq.	84.07644	147.7794	0.863781	141.4212	2036.51
HH Noncancer Ground-surface	toluene eq.	0	0	6.44E-07	0.189627	0
HH Noncancer Root-Zone	toluene eq.	0	0	1.47E-06	0.435114	0
HH Criteria Air-Point Source	PM2.5 eq.	0.001061	0.001029	6.294918	0.000339	0.024571
HH Criteria Air-Mobile	PM2.5 eq.	0.001282	0.001245	7.610988	0.00041	0.029709
Eutrophication	N eq.	0.001337	0.001454	6.716592	0.000688	0.031482
Ozone Depletion	CFC-11 eq.	7.01E-07	1.9E-06	3.04E-10	6.9E-07	7.06E-07
Ecotoxicity	2,4-D eq.	2.400638	4.102815	0.029294	6.100475	69.06588
Smog	NOx eq.	0.025615	0.024859	151.6503	0.008536	0.595765

3.0 Comparison Between Construction Stage and Production Stage:

However if all the 14 impacts are compared between production and construction stage, almost all the impacts are contributed from the production stage except on the two impacts that is HH cancer (over 90%) and HH noncancer (almost 70%). These two impacts are due to the release of dioxins during the course of producing steel.

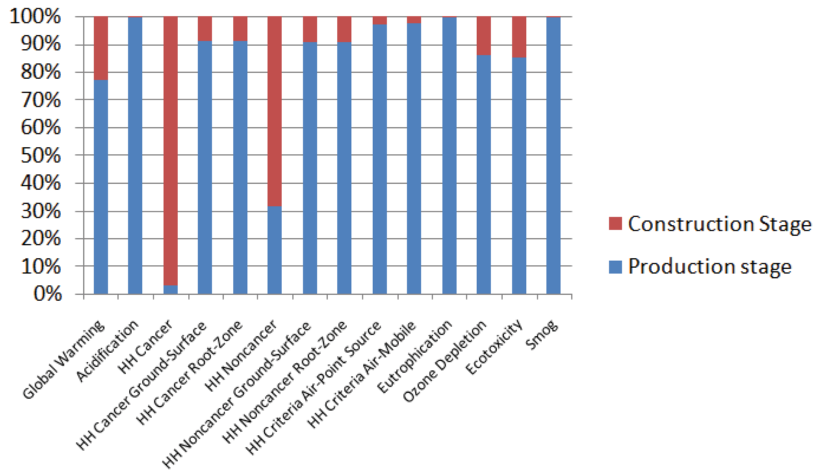

Fig. 5: Perbandingan antara production stage and construction stage

4.0 Conclusion and Recommendation:

In the process of producing clean drinking water, impact are created during the construction or production stage. However, the impact of production stage is greater in comparison to the construction stage. At the production stage, the weakness detected is on the use of PAC, lime and electricity. But at construction stage, the process of producing steel is the main cause on the impact likewise HH cancer and HH noncancer. The process of producing PAC releases Nitrogen oxides and Sulphur oxides which contributes to five types of impacts that is acidification, HH criteria air – point, HH criteria air – mobile, euthrophication and smog. PAC is an alternative. Alum is a substance which can replace PAC. Previous research shows that Alum is much better because the impact is minimum (Amir Hamzah, Noor Zalina, & Abdul Halim, 2008a, 2008b; Amir Hamzah, Noor Zalina, & Abdul Halim, 2009). The three impacts can be eliminated if the PAC is replaced with Alum.

In the production of lime, the four main impact are HH cancer ground - surface, HH cancer root – zone, HH noncancer ground – surface and HH noncancer root –zone) which is due to the emissions released during waste treatment (drilling waste to land farming) such as Arsenic and Aluminum.

However in the course of generating electricity, four highest impact contributes to global warming, HH cancer, HH noncancer dan ecotoxicity. Early research shows the comparison between a few types of electricity generation found that .photovoltaic, hydro and uranium is better from electricity generation using fossil fuel (Amir Hamzah, Noor Zalina, & Abdul Halim, 2009).

Although the impact from the construction stage is much lesser that production stage, still there exist a few problems in the production of building materials. Among the building materials, the process of producing steel gives great impact. The process of producing steel contributes to the impact on HH noncancer and HH cancer. Now, the latest idea is to replace the reinforcement steel with fibre reinforced plastics (FRPs). These materials, which consist of glass, carbon or aramid fibres set in a suitable resin to form a rod or grid, are well accepted in the aerospace and automotive industries and should provide highly durable concrete reinforcement (Clarke, 1998). However, before this alternative is considered to be more friendly to environment or with par with the quality of steel, it should undergo LCA.

REFERENCES

Amir Hamzah, S., M. Noor Zalina and S. Abdul Halim, 2008a. *Life Cycle Impact Assessment (LCIA) of Potable Water Production.* Paper presented at the The National Conference in Enviroment and Health, Kota Bharu, Kelantan.

Amir Hamzah, S., M. Noor Zalina and S. Abdul Halim, 2008b. *Life Cycle Impact Assessment (LCIA) of Potable Water Production in Malaysia: A Comparison between Different River Class.* Paper presented at the The Eight Conference on Ecobalance 08, Tokyo Big Sight, Japan.

Amir Hamzah, S., M. Noor Zalina and S. Abdul Halim, 2009. Life Cycle Assessment (LCA) in Potable Water Production: An analysis of greenhouse gases emission from chemicals and electricity usage in water treatment in Malaysia. Asian Journal of Water, Environment and Pollution, 6(3): 27-34.

Bare, J.C. and T.P. Gloria, 2008. Environmental impact assessment taxonomy providing comprehensive coverage of midpoints, endpoints, damages, and areas of protection. Journal of Cleaner Productionl, 16: 1021-1035.

Bare, J.C., P. Hofstetter, D.W. Pennington and H.A. Udo de Haes, 2000. Life Cycle Impact Assessment Workshop Summary. Midpoints versus Endpoints: The Sacrifices and Benefits. The International Journal of Life Cycle Assessment, 5(6): 319-326.

Bare, J.C., G.A. Norris, D.W. Pennington and T. McKone, 2003. TRACI: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts Journal of Industrial Ecology, 6(3): 49-78.

Bovea, M.D. and A. Gallardo, 2006. The influence of impact assessment methods on materials selection for eco-design. Materials and Design, 27: 209-215.

Clarke, J., 1998. Concrete Reinforced with Fibre Reinforced Plastic. Materials World, 6(2): 78-80.

Dreyer, L.C., A.L. Niemann amd M.Z. Hauschild, 2003. Comparison of three different LCIA methods:EDIP97, CML2001 and Eco-indicator 99. Does it matter which one you choose? The International Journal of Life Cycle Assessment, 8(4): 191-200.

Guinée, J.B., 2002. *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards*: Springer.

Heijungs, R., M. Goedkoop, J. Struijs, S. Effting, M. Sevenster and G. Huppes, 2003. Towards a life cycle impact assessment method which comprises category indicators at the midpoint and the endpoint level. Report of the first project phase Design of the new method [Electronic Version]. Retrieved 7 Mac 2007, from http://www.leidenuniv.nl/cml/ssp/publications/recipe_phase1.pdf

ISO14000, 2000. *Malaysian standards handbook on environmental management: MS ISO 14000 Series - 2nd Ed*. Shah Alam, Malaysia: SIRIM.

ISO 14040:2000, 2005. *Environmental management-Life cycle assessment-Principle and framework*. Malaysian standards handbook on environmental management: MS ISO 14000 Series 2nd Ed, pgs ii-iii. Shah Alam: SIRIM Berhad.

Jolliet, O., A. Brent, M. Goedkoop, N. Itsubo, R. Mueller-Wenk, C. Peña, *et al*., 2003. Life Cycle Impact Assessment Programme of the Life Cycle Initiative. Final report of the LCIA Definition study [Electronic Version]. Retrieved 17 September 2007, from http://lcinitiative.unep.fr/includes/file.asp?site=lcinit&file=F7BF1ABF-8B98-4A95-9FDE-3E32EB7C4EC4.

Jolliet, O., M. Margni, R. Charles, S. Humbert, J. Payet, G. Rebitzer, *et al*., 2003. IMPACT 2002+: A New Life Cycle Impact Assessment Methodology. The International Journal of Life Cycle Assessment, 8(6): 324-330.

Jolliet, O., R. Müller-Wenk, J. Bare, A. Brent, M. Goedkoop, R. Heijungs, *et al*., 2004. The LCIA midpoint-damage framework of the UNEP/SETAC life cycle initiative. The International Journal of Life Cycle Assessment, 9(6): 394-404.

Josa, A., A. Aguado, A. Cardim and E. Byars, 2007. Comparative analysis of the life cycle impact assessment of available cement inventories in the EU. Cement and Concrete Research, 37: 781-788.

Koroneos, C., A. Dompros, G. Roumbas and N. Moussiopoulos, 2005. Advantages of the use of hydrogen fuel as compared to kerosene. Resources, Conservation and Recycling, 44: 99-113.

Miettinen, P. and R.P. Hamalainen, 1997. How to benefit from decision analysis in environmental life cycle assessment (LCA). European Journal of Operational Research, 102: 279-294.

Moberg, G. Finnveden, J. Johansson and P. Lind, 2005. Life cycle assessment of energy from solid waste-part 2: landfilling compared to other treatment methods. Journal of Cleaner Production, 13: 231-240.

Ntiamoah, A. and G. Afrane, 2008. Environmental impacts of cocoa production and processing in Ghana: life cycle assessment approach. Journal of Cleaner Production, 16: 1735-1740.

Ortiz, O., C. Francesc and G. Sonnemann, 2009. Sustainability in the construction industry: A review of recent developments based on LCA. Construction and Building Materials, 23: 28-39.

Pennington, D.W., J. Potting, G. Finnveden, E. Lindeijer, O. Jolliet, T. Rydberg, *et al*., 2004. Life cycle assessment part 2: Current impact assessment practice. Environment International, 30: 721-739.

Sastry, C.A., 1996. *Water Treatment Plants*. New Delhi: Narosa Publishing House.

Sleeswijk, A.W., L.F.C.M. van Oersc, J.B. Guinée, J. Struijsd and M.A.J. Huijbregtsb, 2008. Normalisation in product life cycle assessment: An LCA of the global and European economic systems in the year 2000. Science of the Total Environment, 390: 227-240.

Soares, S.R., L. Toffoletto and L. Deschenes, 2006. Development of weighting factors in the context of LCIA. Journal of Cleaner Production, 14: 649-660.