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Life-cycle assessment of flash pyrolysis of wood waste

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ABSTRACT

This work analyzes a process known as flash pyrolysis, which produces bio fuels using biomass for power generation. A life-cycle assessment of flash pyrolysis of wood waste was conducted to study whether a flash pyrolysis plant set up locally would be environmentally friendly. The results obtained show that the process of flash pyrolysis of wood waste is in fact environmentally friendly, and the process has little contribution to the environment. However, efforts still have to be made to address the global warming potential issue. Continuous research and developments must be carried out to further reduce the global warming potential of the flash pyrolysis.

1. Introduction

Manufacturers and researchers increasingly pay attention to the impacts of manufacturing processes on our environment. There has been more interest in manufacturing products using recycled materials, making the manufacturing technologies more environmentally and economically attractive (Ayrilmis et al., 2009). Many articles discuss the search for environmentally and economically attractive materials (Strachota et al., 2008), and the need to manufacture and process lead-free materials in the microelectronics industry (Arulvanan and Zhong, 2006; Zhong et al., 2007a,b; Chan et al., 2003; Arulvanan et al., 2006; Zhong, 2008) as lead is an environmental pollutant and has serious health impacts (Chidambaram et al., 2009). Many regulations demand a reduction in environmental and health impacts of the materials used in manufacturing (Kesters et al., 2009). One key objective of the environmental policies is to integrate economic growth, welfare and environmental sustainability (Tarantini et al., 2009; Hubacek et al., 2009; Dovì et al., 2009; Kaditi, 2009). Because global trade agreements become more stringent, obedience to environmental regulations for manufacturers becomes more expensive (Hubbard et al., 2008). Actions must be taken as early as possible for the design of energy-using products to reduce their overall environmental impacts (Yung et al., 2009).

The most serious problem resulted from power generation using fossil fuels is release of acid gases (Yang et al., 2009). Acid rain and global warming result from the burning of fossil fuels, and the world has seen many climate changes leading to bad consequences (Feenstra, 1998; Battaglini et al., 2009). The public is increasingly aware of climate changes and many people re-consider their life-style and energy usage choices (Fleck and Huot, 2009). Global warming is a threat to our natural systems in all regions (Giannakopoulos et al., 2009), and thus has resulted in worldwide research efforts to reduce CO_2 emissions (Milovic et al., 2008). One technology researched is flash pyrolysis to produce bio-oil.

The reduction in greenhouse gas emissions has become an important part in the waste management and the energy industries, and there is a change from disposing of wastes in landfills to recycling of waste materials (Wittmaier et al., 2009). Renewable energy has won the legislative support from governments in many countries (Martinez et al., 2009). There is rapid growth in wind power due to its importance for sustainable development (Weinzettel et al., 2009). Although power generation using a photovoltaic system is free from greenhouse gas emissions and fossil fuel use, the energy and emissions involved in the manufacturing, transport and disposal of the elements of the system must be considered (Garcia-Valverde et al., 2009).

Wood waste management is important to enhance sustainability standards (Daian and Ozarska, 2009; Salazar and Meil, 2009). Wood waste includes wood residues from the manufacture, use or disposal of wood products (Taylor et al., 2009). Certain products such as medium density fiber boards can be made out of

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wood waste fibers (Davim et al., 2009). A wood-based biomass comes from wood waste, tree barks or agricultural residues, has energy from the solar energy stored by photosynthesis, and can be burnt to make fuels (Klass, 1998). Interest in biomass-based fuels has been re-boosted because of oil shortage and environmental deterioration (Yu and Tao, 2009a). The promotion of biomass aims at reducing CO_2 emissions from energy harvesting (Solli et al., 2009).

Technologies to convert biomass into energy can be divided into thermal and chemical conversion technologies (Biomass Energy Centre, 2008). Thermal conversion includes direct combustion to generate heat for power (Nan et al., 1994), gasification to breakdown biomass into gases (Biomass Energy Centre, 2008; Purohit, 2009), and pyrolysis to produce gas, char and liquid (Nan et al., 1994). Chemical conversion includes anaerobic digestion using bacteria to breakdown biomass into biogas, and fermentation to produce alcohol (Biomass Energy Centre, 2008). Thermal conversion of waste to energy becomes more and more important because of a number of advantages (Stehlík, 2009). A growing interest in renewable energy sources leads to intensive research on thermal conversion techniques such as gasification and pyrolysis (Janse et al., 2000).

Pyrolysis is a thermal decomposition process in which biomass is decomposed by heat in the absence of oxygen, leading to the production of charcoal, char, liquid and gaseous products (Sheth and Babu, 2009). Methanol is one most valuable product and can replace conventional gasoline and diesel fuels (Demirbas, 2002). The bio-oil has a higher energy density and is easy to store and transport (Xu et al., 2009). In slow pyrolysis processes, char production is maximized and the heavy metals are kept in the remaining solid matrix (Ratte et al., 2009). Fast or flash pyrolysis is a method to maximize the liquid product yield (Pokorna et al., 2009), and is the most effective and commercially available technology for the production of liquid fuel from biomass (Deng et al., 2009; Bech et al., 2009; Dupont et al., 2009).

Bio-fuel is an improvement in terms of fossil CO_2 emissions, but the technology may also have negative environmental impacts (Lardon et al., 2009). Using of bioenergy does not automatically guarantee sustainable production, conversion and distribution of it (Buchholz et al., 2009; Ponton, 2009; Martin et al., 2009; Hall et al., 2009). The bio-fuel consumption may increase greenhouse gas emissions due to land-use changes (Bringezu et al., 2009). Therefore, life cycle assessment (LCA) of the technology is needed. LCA is a useful tool for assessing the overall environmental impact of a process or product (Xu et al., 2008; Humbert et al., 2009; Zhong et al., 2009). It has been introduced to many fields including waste management and treatment, and bio-fuels (Kiatkittipong et al., 2009; Benetto et al., 2009; Laner, 2009; Ribeiro and da Silva, 2010; Ometto and Roma, 2010; Yu and Tao, 2009b).

In this study, a life-cycle assessment was conducted on the process of flash pyrolysis which yields the desired pyrolytic oil or bio oil from wood waste, in terms of the impacts on the environment.

2. The methodology used

The methodology used in this study is the LCA technique based on the ISO 14040 series of standards. An LCA study consists of four phases: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation (ISO, 2006).

2.1. Goal and scope definition

The goal and scope of an LCA study should be clearly defined and consistent with the application (ISO, 1998). The goal of this LCA study is to identify the environmental impact of the process of converting biomass from waste wood to pyrolytic oil. Fig. 1 shows the system boundary, defined by the dashed-line box. Only the main processes are shown in Fig. 1. For example, the detailed sub-processes such as char combustion and cylone, flash pyrolysis and char cyclone, quenching, pumping and filtration, precipitation, excess gas combustion, and gas combustion sub-processes belonging to the main process of the "flash pyrolysis plant" are not shown in Fig. 1, but are listed in Table 1 in section 2.2. One current practice of waste disposal in Singapore is incineration of waste at several incineration plants and disposal of the ash and slag at a landfill site after the incineration. It is assumed that the wood waste studied in this work is separated from general waste (residential, institutional, commercial and municipal services wastes) at the waste management centers in the incineration plants and then transported to a briquette plant, as shown in Fig. 1.

2.2. Inventory analysis

The LCI (life cycle inventory) analysis phase is related to the calculations and collection of data (ISO, 1998). A number of reference sources and reasonable assumptions are used in the calculations. A model is established using a SimaPro software system (PRe Consultants, 2009). Data from the database available in SimaPro are used for the modeling of transportation.

In the briquette plant, the bulky wood is sized into small pieces (<3 mm), which then are pressed into briquettes. 37 kW of power is supplied for 1800 kg/h of briquetting (Grover and Mishra, 1996). The pyrolysis process converts biomass particles into gases, solid char particles and condensable pyrolytic vapor by heating the biomass in a reactor in the absence of oxygen. The vapor is quenched to form pyrolytic oil. The process conditions include very short residence time < 2 s and high heating rates of 450 to 600 °C (Nan et al., 1994). The initial step of flash pyrolysis occurs in the reactor, which has no oxygen (as low amount as possible) and a high temperature of about 500 °C, to produce pyrolytic vapors (Bridgwater, 2005), which contain carbon ions, hydrocarbons and organic products (Brown and Holmgren, 2006).

The flash pyrolysis plant has a char combustor which has a sole purpose of burning char for the main flash pyrolysis reactor (Bridgwater, 2005). 57.1 kWh power is supplied to heat the air intake which is mixed with the fed char to allow combustion to take

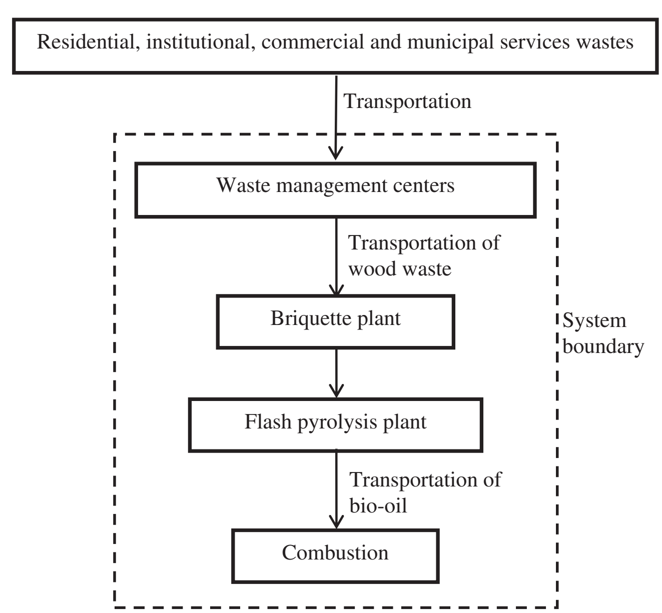

Fig. 1. System boundary defined by the dashed-line box.

Table 1
LCI of char combustion and cylone, flash pyrolysis and char cyclone, quenching, pumping and filtration, precipitation, excess gas combustion, and gas combustion (Peacocke et al., 2006; Zaki, 2009).

Process	Input	Data (unit/h)	Output	Data (unit/h)
Char combustion & cylone	Char + ash	194.1 kg	Cooled gas	2536.7 kg
	Hot air	2030.4 kg	Ash	0.5 kg
	Power	57.1 kW	Unburnt char	6.3 kg
			Heat	3220 J/g
Flash pyrolysis and char cyclone	Dry briquettes	2250.7 kg	Filtered pyrolysis gas	4106.9 kg
	Fluidizing gas	2118 kg	Char + ash	262.3 kg
	Heat	3220 J/g	Heat	369.5 J/g
Quenching	Filtered pyrolysis gas	4106.9 kg	Pyrolysis liquid	165727.1 kg
	Quenching liquid	163405 kg	Non condensable vapors	2860.4 kg
	Precipitation liquid	541.1 kg		
	Power	40 kW		
Pumping & filtration	Pyrolysis liquid	165727.1 kg	Pyrolytic oil	1782.9 kg
	Power	6 kW	Quenching liquid	163403.5 kg
Precipitation	Non condensable vapors	2860.4 kg	Excess gas	697.6 kg
			Precipitation liquid	541.1 kg
			Hot process gas	1627.6 kg
Excess gas combustion	Hot air	1451.4 kg	Inert gas	2149.4 kg
	Excess gas	697.6 kg		
	Power	57 kW		
Gas combustion	Hot process gas	1627.6 kg	Fluidizing gas	2118 kg
	Hot air	490.1 kg		
	Power	57 kW		

place (Peacocke et al., 2006). The resulting product is heating gas which consists of various gases and some un-burnt char and ashes. The heating gas is then filtered in an ash cyclone where the un-burnt char is collected to be re-fed into the combustor while the ash is filtered as waste product and the cooled gas released. A total of 3220 J/g heat produced is used for the flash pyrolysis reactor (Reed and Gaur, 1997). Table 1 shows the LCI of char combustion and cylone, flash pyrolysis and char cyclone, quenching, pumping and filtration, precipitation, excess gas combustion, and gas combustion (Peacocke et al., 2006; Zaki, 2009), and Table 2 shows the LCI of pyrolytic oil combustion process (Zaki, 2009). The heat of pyrolysis reaction, h (J/g), can be calculated using the following equation (Reed and Gaur, 1997),

Table 2
LCI of pyrolytic oil combustion process (Zaki, 2009).

Input	Data (unit/h)	Output	Data (unit/h)
Pyrolytic oil	1782.9 kg	Particulate	0.65 kg
Power	879 kW	Sulphur dioxide	0.03 kg
		Nitrogen oxide	0.54 kg
		Carbon monoxide	0.01 kg
		Carbon dioxide	607.22 kg
		Oxygen	451.6 kg
		Water	722.85 kg
		Heat	100 kW

$$h = 3142F_c - 553 \tag{1}$$

where F_c is weight fraction of char produced. In this study, the weight fraction of char for 2 ton wood waste is $F_c = 255/4369.2 = 0.0584$. Hence, $h = -369.5$ J/g and is negative because it is an exothermic reaction, meaning the amount of heat given off from the flash pyrolysis reaction is 369.5 J/g.

If the flash pyrolysis plant is to be located in Singapore, its power consumptions may be supplied from the power grid. Therefore, in the LCA study of this scenario, the electricity grid emission factors (National Environment Agency Singapore, 2009) have to be used for the calculations based on the information from the National Environment Agency of Singapore, and any usage of electricity from the power grid would have certain carbon dioxide and methane emissions to the environment.

2.3. Impact assessment

The life cycle impact assessment generally has several mandatory elements (choosing of characterization methodology and impact categories indicators, calculating of the indicator results, etc.) that convert LCI results to the collection of indicator results for different impact categories. There may be optional elements for weighting or normalization of the indicator results, etc. (ISO, 2000). In this study, the environmental design of industrial products (EDIP) methodology and 15 impact categories were chosen to be used. The impact categories are global warming potential (GWP), ozone depletion, acidification, eutrophication, photochemical smog, ecotoxicity (water chronic or acute, soil chronic), human toxicity (air, water, soil), waste (bulk, hazardous, radioactive), and slag/ash. The impacts are calculated using the SimaPro LCA software tool (PRe Consultants, 2009), and are presented in section 3. The EDIP method has relatively simple assessment of ecotoxic and human impacts based on key properties of the pollutants (Larsen et al., 2009; Munoz et al., 2009).

2.4. Interpretation

An LCA study completes with the interpretation phase by evaluating the results of the life cycle impact assessment of the product system and presenting them to meet the requirements described in the goal and scope of the LCA study (ISO, 2000). The assessment results of this work are interpreted and discussed in section 3.

3. Results and discussion

Fig. 2 shows the characterization of the impacts of burning pyrolytic oil. Each of the respective impact categories amounts to 100%. The impacts of the inputs (the pyrolytic oil and power supply) and the outputs (particulate emissions) of the combustion process are compared. The burning process of pyrolytic oil to generate power affects the environment in terms of a number of impact categories.

Firstly, particulate emissions from the burning of pyrolytic oil have GWP of about 17%, while the chemicals in pyrolytic oil contribute to about 19% GWP. But, the bulk of the effect on global warming comes from the power supplied to burn the oil, which is 64%. The power needed for the combustion of pyrolytic oil is the main contributor to global warming potential in this burning process. This power is also the dominant factor causing photochemical smog, 81% responsible, as shown in Fig. 2. The rest of this impact (photochemical smog) is caused by the chemicals in pyrolytic oil.

Secondly, the chemicals or organics in pyrolytic oil actually result in the most impacts in terms of a number of impact categories. It is 100% responsible in causing the impacts on ozone depletion, ecotoxicity (water chronic, water acute, and soil chronic), human toxicity (water and soil), and bulk waste. Hence, it is important for

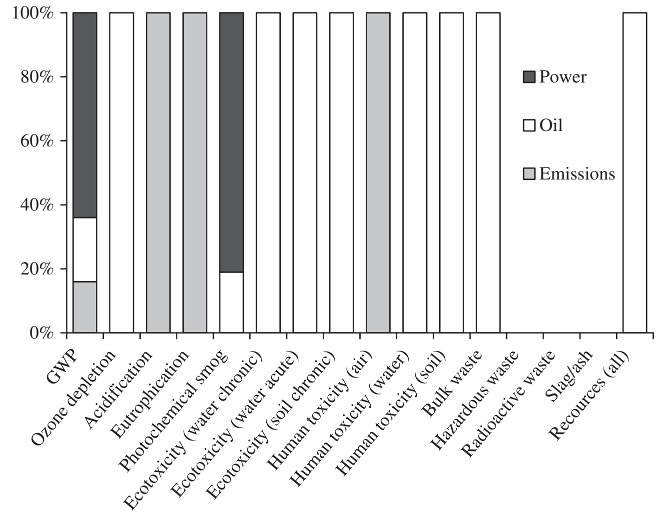

Fig. 2. Characterization of the impacts of burning pyrolytic oil.

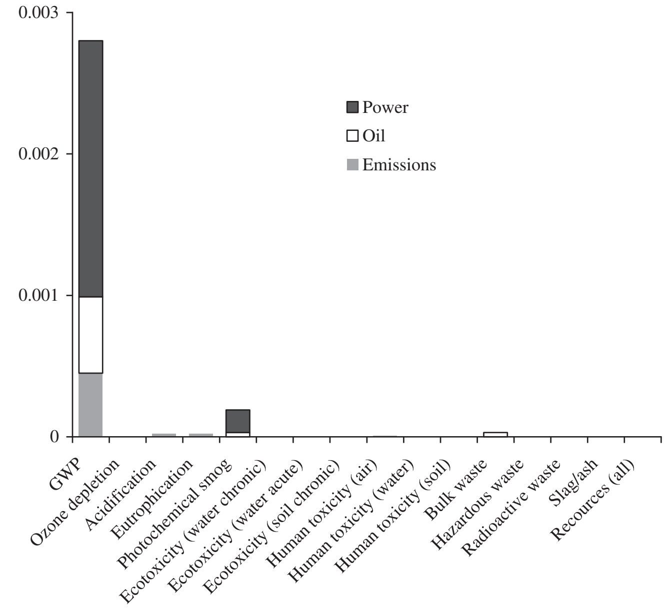

Fig. 3. Normalization of the impact values of burning pyrolytic oil.

the flash pyrolysis plant to be able to prevent any leakage of the oil to the surrounding eco system due to the potential dangers of its constituent chemicals.

Lastly, the emissions from the combustion of pyrolytic oil have not only a minor effect on GWP but also a significant role (100%) in causing impacts on acidification, eutrophication and human toxicity (air). It is thus essential for the plant to treat these airborne emissions with care and also ensure that proper filtration of these emissions is carried out.

Next, all of the impact scores were divided by a reference score for each impact category to investigate whether the impacts calculated in the characterization would be significant, and this benchmarking step is known as normalization. In the EDIP method used in this study, normalization is based on person equivalents (Danish Environmental Protection Agency, 2003), meaning the reference score is that of one average European person per year for an impact category. Fig. 3 shows the normalization of the impact values of burning pyrolytic oil. As shown in this figure, GWP impact category has a normalized score of 0.0028 while the normalized scores of the other impact categories are smaller than 0.0002. Although the burning of pyrolytic oil seems to contribute to global warming potential, the normalized score of 0.0028 is relatively small.

Fig. 4 shows a summary of single scores in mili-point (mPt) of all the impacts calculated for the combustion of pyrolytic oil. The particulate emissions that are given off to generate power from burning of pyrolytic oil are not the most damaging, but the amount of electricity to burn the oil is. The amount of electricity supplied would result in the emissions of about 460 kg of CO_2 and 2.37 kg of methane. The large amount of carbon dioxide gas is the main factor behind the impact this process has on GWP. Thus, the flash pyrolysis plant should look into a more efficient engine which would need less electricity to burn the same amount of pyrolytic oil.

Fig. 5 shows the characterization of the impacts of the flash pyrolysis process. The impacts of the three inputs and one output of the process are compared. The three inputs are fluidizing gas, dry briquettes and the heat supplied to the reactor, while the output is the pyrolysis gas. Pyrolysis gas does not have any impact on any of the impact categories. This may be due to the fact that the whole pyrolysis gas is used as an input for the next process which is the filtration process where pyrolysis gas is heavily filtered. The dry wood briquettes, when they are burnt, have impacts on all the categories. The fluidizing gas, which is made up of nitrogen, water and carbon dioxide, has certain impacts on GWP and photochemical smog with impact percentages of 11% and 14%, respectively. The heat energy supplied to the flash pyrolysis reactor from the char combustor is 33% responsible for the GWP and only 9% responsible for the effect of photochemical smog.

Fig. 6 shows the normalization of the impact values of the flash pyrolysis process. Except for GWP and effect of photochemical smog, the impacts of the other categories are insignificant after they are normalized. The normalized impact value (0.0000019) under the photochemical smog category is very small and can be considered insignificant. The process of flash pyrolysis has an impact on the global warming, but the impact value of 0.0000265 can also be considered small.

Fig. 7 shows a summary of single scores in micro-point (μPt) of all the impacts calculated for the process of flash pyrolysis. Out of the three inputs and one output of the process, the dry briquettes have the highest potential to be environmentally harmful as they

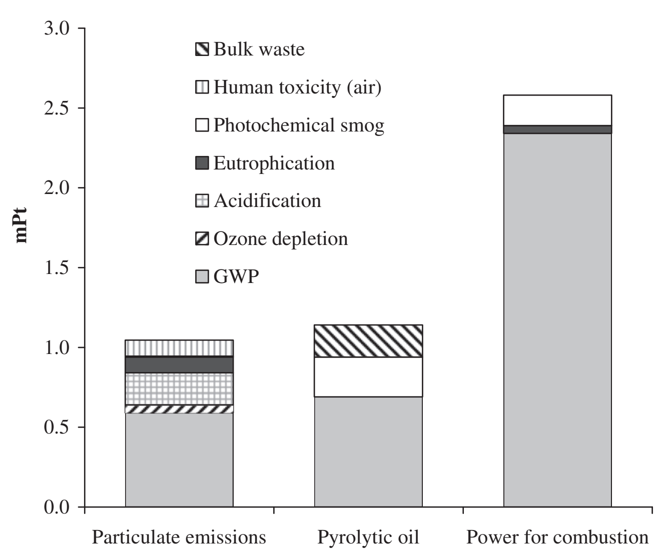

Fig. 4. Single scores in mPt (milipoint) of all the impacts calculated for the combustion of pyrolytic oil.

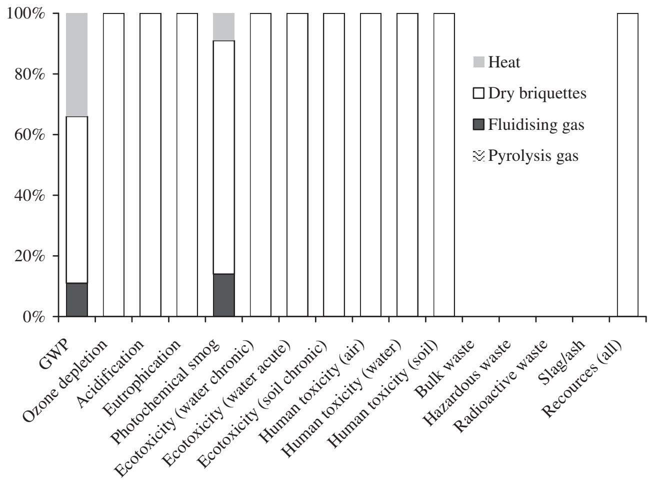

Fig. 5. Characterization of the impacts of the flash pyrolysis process.

have the highest score of 21.5 μPt. Fluidizing gas has a score of 3.65 μPt, and this indicates how the flash pyrolysis plant is environmentally friendly because fluidizing gas is actually one of the recycled products of the plant. This means that as the raw input passes along the process flow, it gets "cleaned" before being either emitted or recycled back as the inputs of certain processes.

Based on the charts obtained, it can be said that if a flash pyrolysis plant is set up in Singapore, it would have an impact on Singapore's environment especially under the category of global warming potential. This is because the category of global warming potential has the highest scores for both the process of flash pyrolysis of the wood waste and the combustion of the product. The impacts in the other categories are insignificant and thus pose very little threat.

In view of the global warming potential effect due to the plant's processes, it is important for the plant to minimize or control this effect. For this to materialize, the root of the problem of global warming needs to be addressed. As already known, GWP is caused by greenhouse gases such as carbon dioxide, methane and nitrous oxides. For the flash pyrolysis plant, there are no emissions of nitrous oxides, and thus more efforts have to be made concentrating on reducing the amount of carbon dioxide and methane emissions. Methane is not a product of any processes considered and is only released as part of the generation of the electricity to supply power for certain processes considered. The following ways may be further considered:

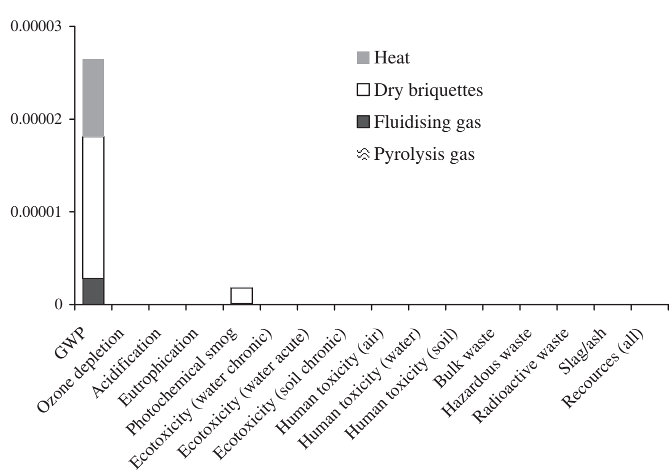

Fig. 6. Normalization of the impact values of the flash pyrolysis process.

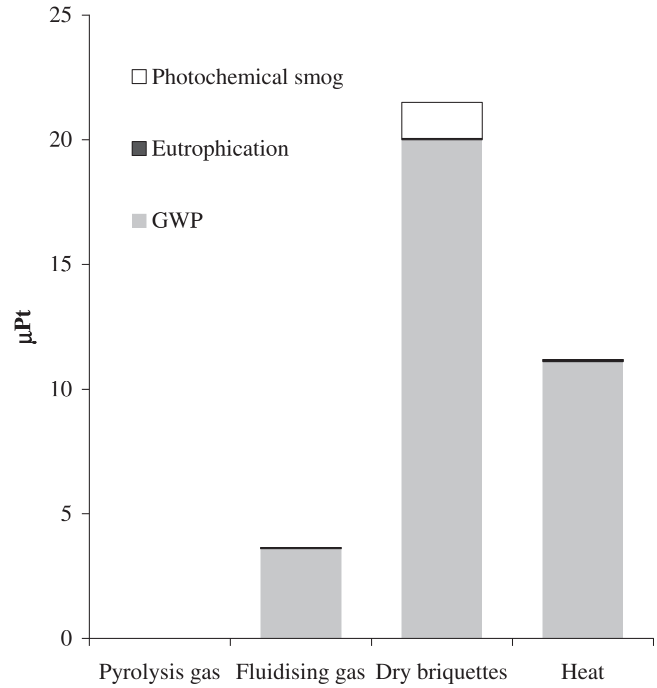

Fig. 7. Single scores in μPt (micropoint) of all the impacts calculated for the flash pyrolysis process.

1) Improve the filtration system to reduce the amount of carbon dioxide released into the atmosphere.
2) Improve the efficiency of heat transfer between mediums in the reactor so that less electricity is needed. This would mean less carbon dioxide and less methane released since these gases are produced to generate electricity in the power grid.
3) Improve the process efficiency so that less waste materials are produced and more of these wastes are able to be recycled back into the process flow to be of use. This way, there will be less wastage and cleaner waste products.
4) Perform further LCA studies and compare the different results considering alternative renewable sources of power (including the electricity generated using the bio-fuel produced) to replace the grid power, process integration techniques to improve the heat exchange within the reactor to reduce the amount of energy required, sensitivity analyses, etc. in future studies. With the electricity provided from the grid minimized, further reduction of the environmental impacts can be expected.

4. Conclusion

A flash pyrolysis plant which harnesses wood waste to produce pyrolytic oil for generating power is environmentally friendly. Based on the LCA done, the results support this claim. However, one must be aware that efforts still have to be made to address the global warming potential issue. This is because being environmentally friendly does not mean it is totally clean. Continuous research and developments also have to be carried out to further reduce the global warming potential of the flash pyrolysis. As a future study, an environmental impact comparison of the flash pyrolysis technology with other technologies such as the present production of electricity and/or other renewable energy technologies can be conducted, and with the electricity provided from the grid reduced, further reduction of the environmental impacts can also be expected.

Hopefully, more countries will make more efforts to look into alternative methods of generating power from the massive amounts of wastes they generate. Only then can the usage of burning of fossil fuels be reduced and the harmful effects to the environment eventually be minimized.

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