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GHG Emissions of Incineration and Anaerobic Digestion: Electricity Mix

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Waste to energy (WtE) is one of the suitable alternatives in handling municipal solid waste (MSW). This study assesses the GHG emissions (CO_{2eq}) of incineration and anaerobic digestion (AD) under different electricity production mix. The electricity production mix of China, Malaysia, Japan, Russia, UK, US (East), Czech Republic, Germany, France and Finland were considered. Incineration has a lower net CO_{2eq} emission in China and Malaysia. However, the AD is environmentally preferable than incineration in Russia, Japan, Czech Republic, Germany, US (East), UK, Finland and France. The net CO_{2eq} emission of incineration in China (9.41 kg CO_{2eq}/t MSW) is lower than a country with greener electricity mix e.g. France (401.76 kg CO_{2eq}/t MSW) where the main electricity source is nuclear. This is due to the higher avoided CO_{2eq} emission compare to generate electricity from fossil fuel. Electricity produces from the WtE process is identified as the major factors in affecting the net CO_{2eq} emission than the other two assessed factors (waste collection and transportation (distance), the efficiency of the WtE process). This suggests energy efficiency plays a significant role in enhancing the net CO_{2eq} emissions and to reduce the carbon intensity of WtE.

1. Introduction

Municipal solid waste (MSW) is one of the challenges with the development of economic and population. The high variation in the composition complicates the prediction, assessment and the selection of the suitable waste management. Waste to Energy (WtE) is a process that provides two-fold benefits, waste treatment and energy recovery. The environmental performance of different handling approaches of MSW has been commonly assessed. Rajaeifar et al. (2015) assess the environmental impact of five different scenarios in handling MSW. It was found that, in term of global warming potential, anaerobic digestion (AD) poses the greater performance followed by incineration combined with composting, incineration, and AD combined with incineration. Dong et al. (2014) compare the environmental impact of landfill and incineration by including the detailed life cycle. A similar study is also performed in Nigeria by comparing different WtE scenario with the landfilling (Ayodele et al., 2017). The outcome of life cycle assessment is dependent on the system boundaries and the chosen baseline scenario. The contribution of these studies is minimal as the results will be logically positive (Coventry et al., 2016) when compared to the worst scenario (landfilling). The baseline scenario is usually the conventional method of waste disposal- landfill scenario or sometimes energy production- fossil fuels scenario (Nabavi-Pelesaraei et al., 2017). The plus point of WtE has been commonly reported but there is also contrast opinion on the energy efficiency of producing energy from the waste. The environmental sustainability is also a concern although is from the minority. WtE could be a better alternative than landfill in the view of environmental performance. However, it is not certainly having a better environmental performance than generating the energy through fossil fuel. Different factors need to be taken into consideration and the appropriate system boundary is yet to be defined. The assessment from the perspective of energy generation instead of comparing to landfill is still lacking and the effect of electric mix of a country on the environmental sustainability/ feasibility (net CO_{2eq}

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emission) of WtE is yet to be identified. The purpose of this work is to assess the CO_{2eq} emission of different WtE (AD and incineration) by considering the avoided emission from the generated products (electricity, digestate). The impact of the electricity production mix of a country on the net emission CO_{2eq} performance of the WtE processes is discussed. This is to show the interconnected relationship and to further highlight the limitation of considering WtE as an energy generation solution with lower carbon emission. The impacts of waste collection and transportation (distance), WtE process and the electricity produced (hence avoided) from the WtE process on the net CO_{2eq} emission were assessed. This is to identify the dominant factors in affecting the net emission CO_{2eq} performance of the WtE processes.

2. Input data and assessment method

2.1 The net CO_{2eq} emission of WtE and its relationship with energy mix in different countries

The MSW in this study is defined to have 53 % organic material, 11 % paper, 9 % plastic, 3 % glass, 3 % metals, 3 % textiles, 16 % others (UNEP, 2017). The selected WtE treatments are incineration and AD. Three scenarios were evaluated in this study. Among the 1 t of MSW, (a) Scenario 1 = 0.89 t can be treated by incineration, (b) Scenario 2 = 0.64 t treated by AD (c) Scenario 3 = 0.25 t treated by incineration and 0.64 t treated by the AD. The net CO_{2eq} emission is calculated from the perspective of as an energy recovery process, based on 1 t of MSW. The WtE process is view as an alternative solution for energy production (MSW as the substrate) instead of waste treatment. The emission of the untreated MSW which end up in the landfill is not considered in this study. The net CO_{2eq} emission was calculated according to Eq(6), by referring to Eq(1) to Eq(5). Eq(3), Eq(4) and Eq(5) show the avoided CO_{2eq} emission for AD (Scenario 1), incineration (Scenario 2) and combined AD and incineration (Scenario 3). Table 1 shows the input data for the calculation. Figure 1 shows the emission factors of electricity based on electricity production mix (kg CO_{2eq}/ kWh) in different countries. A total of 10 countries including China, Malaysia, Japan, Russia, UK, US (East), Czech Republic, Germany, France and Finland were assessed. Different electricity mix of a country will affect the avoided CO_{2eq} emission from the WtE process and hence the net CO_{2eq} emission.

CO_{2eq} emission of transportation, kg/ t_{MSW}

$$= (F_{cc} \times F_{ef})\, D_c + (F_{ct} \times F_{ef})\, D_t \quad (1)$$

F_{cc} = Fuel consumption factor of waste collection, kWh/ tkm
F_{ef} = Fuel emission factor, kg CO_{2eq}/ kWh
F_{ct} = Fuel consumption factor of waste transporting, kWh/ tkm
D_c = Distance travelled of collection, km
D_t = Distance travelled of transporting, km
One t of MSW was collected/ transported but not all compositions were used for the WtE treatment.

CO_{2eq} emission (kg/ t_{MSW}) of WtE process

$$= E_{tp} \times PW \quad (2)$$

E_{tp} = Emission of treatment process, kg/t_{PW}; AD ($E_{tp\ AD}$) or incineration ($E_{tp\ i}$)
PW =Amount of processed waste, t_{pw}; AD (PW_{AD}) or incineration (PW_i)

Avoided CO_{2eq} emission of AD process, kg/ t_{pw}

$$= (E_{AD} \times PW_{AD} \times EF_c) + (PW_{AD} \times 0.9 \times N_{Dig} \times E_{fer}) \quad (3)$$

E_{AD} = Electricity production factor from AD, kWh/ t_{pw}
PW_{AD} = Amount of processed waste, t_{pw}; AD
EF_c = Emission factors of electricity production mix, kg CO_{2eq}/ kWh; different countries
N_{Dig} = N content in digestate
E_{fer} = Emission from fertiliser production
0.9 = Conversion factor (90 %) of waste to digestate (Fan et al., 2018)

Avoided CO_{2eq} emission (kg/ t_{MSW}) of incineration process, Electricity

$$= (E_i \times PW_i \times EF_c) \quad (4)$$

E_i = Electricity production factor from incineration, kWh/ t_{pw}
PW_i = Amount of processed waste, t_{pw}; incineration

EF_c = Emission factors of electricity production mix, kg CO_{2eq}/ kWh; different countries

Avoided CO_{2eq} emission of combined process, kg/ t_{MSW}

= (E_i x $PW_{0.89\text{-}AD}$ x EF_c) + [(E_{AD} x PW_{AD} x EF_c) + (PW_{AD} x 0.9 x N_{Dig} x E_{fer})] (5)

Eq(6) shows the net CO_{2eq} emission considering the emission from transportation and WtE process.

Net CO_{2eq} emission, kg/ t_{MSW}

= (CO_{2eq} emission of transportation + CO_{2eq} emission of WtE process) - Avoided CO_{2eq} emission (6)

CO_{2eq} emission of transportation is Eq(1), CO_{2eq} emission of WtE process is Eq(2), Avoided CO_{2eq} emission is Eq(3) or Eq(4) or Eq(5)

Table 1: Input data and the source

	Value	Unit	Reference
F_{cc}, Fuel consumption factor of waste collection	12.500	kWh/ tkm	Pöschl et al. (2010)
F_{ef}, Fuel emission factor	0.250	kg CO_{2eq}/ kWh	CarbonTrust (2006)
F_{ct}, Fuel consumption factor of waste transporting	1.083	kWh/ tkm	Pöschl et al. (2010)
D_c, Distance travelled of collection (km)	10	km	Assumed[a]
D_t, Distance travelled of transporting (km)	10	km	Assumed[a]
$E_{tp\ AD}$= Emission of AD process AD	228.500	kg/ t_{PW}	Phong (2012)
$E_{tp\ i}$ = Emission of incineration process	460.000	kg/ t_{PW}	Ritchie and Smith (2009)
PW_{AD}, Amount of processed waste, AD	0.640	t_{pw}	Assumed[b]
PW_i, Amount of processed waste, incineration	0.890	t_{pw}	Assumed[c]
E_{AD}, Electricity production factor from AD	564	kWh/ t_{pw}	Achinas et al. (2017)
E_i, Electricity production factor from incineration	207.200	kWh/ t_{pw}	Murphy and McKeogh (2004)
$PW_{0.89\text{-}AD}$, amount of processed waste for incineration	0.250	t_{pw}	Assumed[d]
N_{Dig}, N content in digestate	0.010	g N/ g digestate	Annachhatre (2012)
E_{fer}, Emission from fertiliser production	3,600	kg CO_{2eq}/ N	Yara HESQ (2014)

[a]The value can be changed based on assumption or the real cases. [b]1 t of MSW consists of 0.64 t of waste suitable for the AD. [c]1 t of MSW consists of 0.89 t of waste suitable for incineration. [d]1 t of MSW consists of 0.64 t of waste suitable for the AD and 0.25 t for incineration

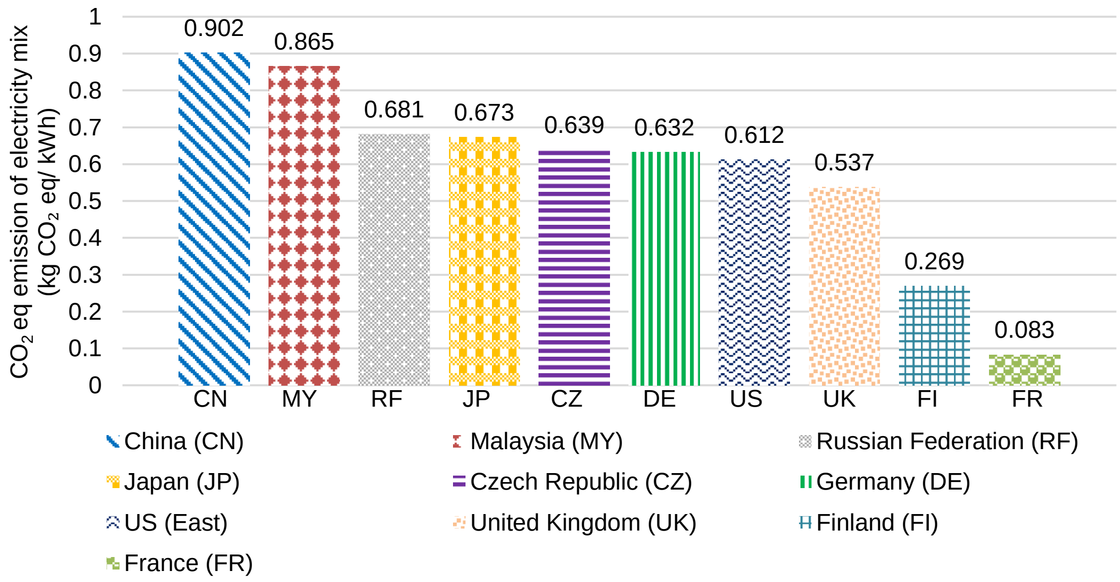

Figure 1: EF_c, Emission factors of electricity based on production mix (kg CO_{2eq}/ kWh) in different countries (extracted from GaBi database, thinkstep, Germany)

2.2 Sensitivity analysis

The effect of changing the value of waste collection and transportation (distance), WtE process and the electricity produced from the WtE process on the net CO_{2eq} emission were assessed. The sensitivity analysis of the mentioned factors were varied within -30 % to +30 % (5 % interval) by applying Eq(1), Eq(2), Eq(4) and Eq(6). Net CO_{2eq} emission of incineration in China is selected as an example. The most significant factor that impacts the net CO_{2eq} emission was identified.

3. Results and discussion

Figure 2 shows the net CO_{2eq} emission of incineration and AD process at different countries. The CO_{2eq}/t emission of MSW increases (Figure 2) with the decreases of emission factors based on electricity production mix of a country (see Figure 1). This highlights the electricity mix in a country could affect the overall environmental sustainability of the incineration and AD treatment for MSW. The greener the current electric mix of a country (especially those dominant by renewable energy), the lower environmental sustainability (higher net CO_{2eq} emission) of electricity could be offered by incineration or AD. The electricity sector in China is dominated by fossil fuel (hard coal), which is known to produce a significant amount of CO_{2eq} emission. The implementation of WtE in China offers a lowest net CO_{2eq} emission, as the emission is avoided from the conventional electricity generation (fossil fuel). The net CO_{2eq} emission of incineration is estimated to be -9.41 kg/ t MSW. France is dominated by nuclear power, as shown in Figure 2, the net CO_{2eq} emission of WtE processes is high.

In this study, the energy is assumed to be used as electricity. The result (environmental sustainability of WtE) can be different if it is also used as heat energy. For example, in France, ~76 % of electricity is from nuclear generation, whereas 100 % of heat generation is from fossil fuels or waste combustion (IEA, 2011). If the energy from the waste (incineration/ AD) is used as heat, it would be environmentally more feasible than being used as electricity. This is with the explanation that the avoided emission from the conventional heat generation (fossil fuels) is higher compared to electric generation (nuclear and other renewables).

Based on Figure 2, incineration has a lower net CO_{2eq} emission in China and Malaysia. However, contrast results were obtained in Russian Federation, Japan, Czech Republic, Germany, US (East), UK, Finland and France. The AD is environmentally preferable in these countries. The changes happened between Malaysia and Russia (see the caution sign in Figure 2) suggest the turning point are between 0.865 and 0.681 kg CO_{2eq}/ kWh (see Figure 1). The AD is preferable when the emission factors of electricity based on production mix in a country are less than 0.681 kg CO_{2eq}/ kWh. This can be explained by the lower amount of CO_{2eq} emission avoided from electricity production while the avoided CO_{2eq} emission from fertiliser production through the utilization of digestate outweigh the net impact.

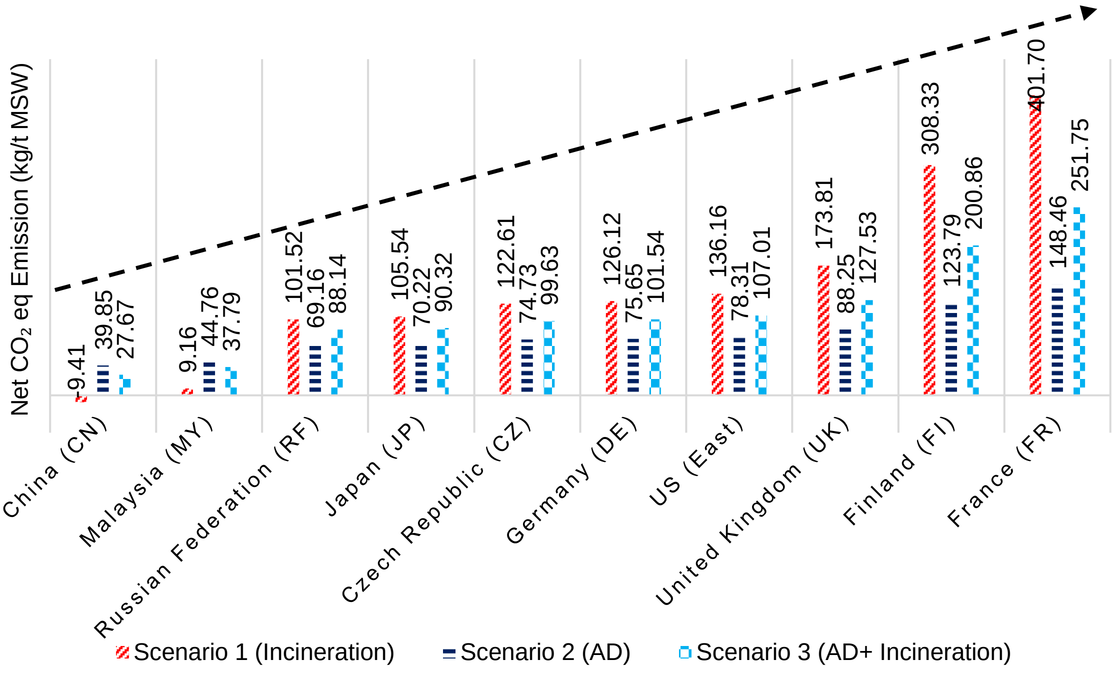

Figure 2: The net CO_{2eq} emission of incineration and AD process at different countries.

Figure 3 shows the net CO_{2eq} emission of incineration in China. The impacts of changing the waste collection and transportation (distance), the efficiency of incineration process, energy production of incineration were illustrated. The longer the waste collection and transportation distance, the higher the CO_{2eq} emission, the higher the net CO_{2eq} emission of incineration. The higher the CO_{2eq} emission of the incineration process (in this study= 460 kg CO_2eq/t_{pw} see Table 1), the higher the net CO_{2eq} emission of incineration. The higher energy production of incineration (in this study = 207.2 kg kWh/t_{pw}, see Table 1), the higher amount of avoided CO_{2eq} emission, the lower the net CO_{2eq} emission of incineration. The value of the mentioned factors (waste collection and transportation, incineration process, energy production of incineration) was varied by -30 to +30 %. As presented in Figure 3, the changes of energy production of incineration give the highest impacts to the net CO_{2eq} emission of incineration (gradient = 4.5277). This highlights the significant role of improving the energy efficiency of WtE to achieve low net CO_{2eq} emission. The distance travelled in waste collection and transportation has the least impact on the overall CO_{2eq} emission.

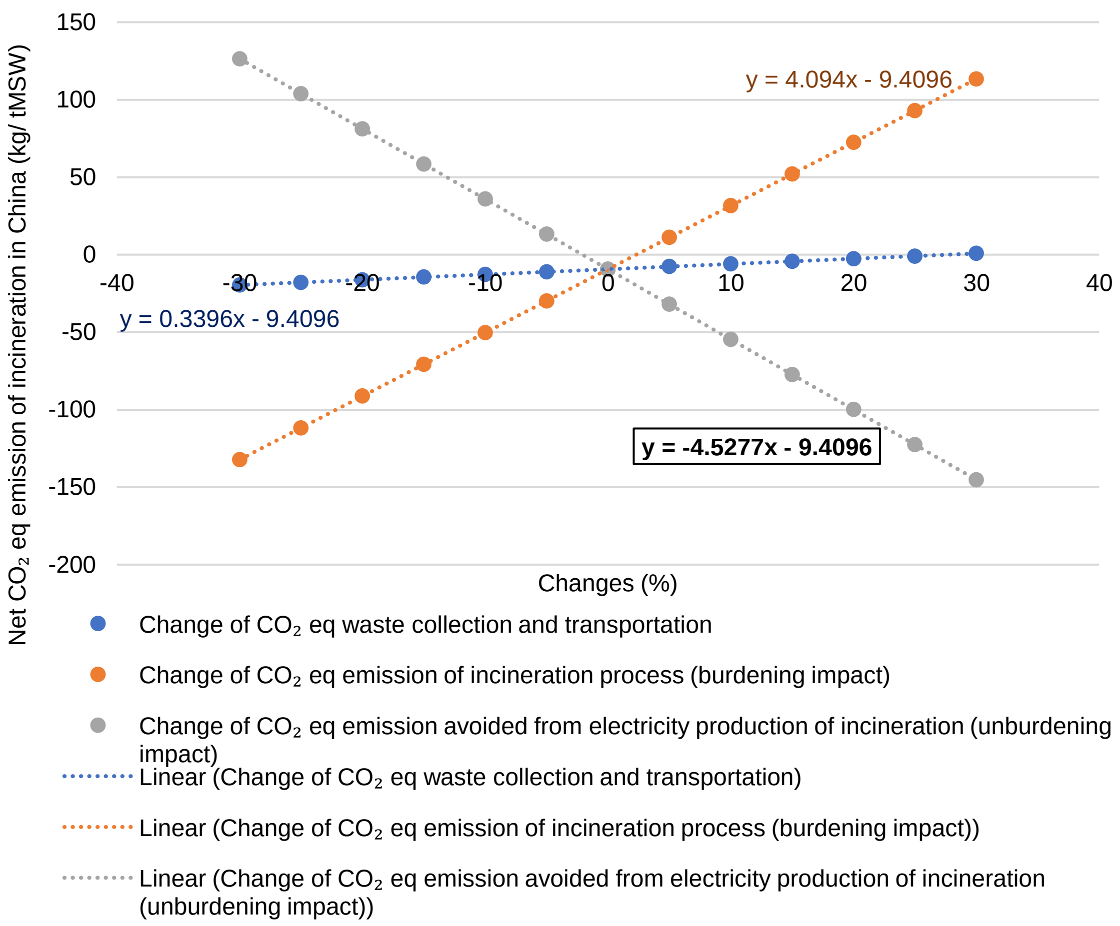

Figure 3: The impact of waste collection and transportation, incineration process, energy production of incineration on the net CO_{2eq} emission of incineration in the selected example (China).

In contrast to study reported by Vaida and Lelaa (2017), this study proposes incineration and AD are more suitable to be deemed as a disposal operation than an energy generating/recovery operation. With the exception of China, where the current electricity production is highly depending on the fossil fuel. Minimisation of GHG emissions through WtE remains an open question. WtE seems to be a waste treatment instead of facilitating the transition towards low-carbon sources. This is especially for the countries where fossil fuel is not the main energy sources e.g. France.

4. Conclusions

The electricity production practice of a country has a significant impact on the net CO_{2eq} emission of WtE technologies. The higher the renewables energy share or efficiency of electricity production technology, the lower the environmental feasibility of the WtE implementation. The electricity sector in China is dominated by fossil fuel (hard coal). The implementation of WtE in China offers a lowest net CO_{2eq} emission, as the emission is avoided from the conventional electricity generation (fossil fuel). The net CO_{2eq} emission of incineration based on the electricity mix in China is estimated to be -9.41 kg CO_{2eq}/t MSW and AD is 27.67 kg CO_{2eq}/t MSW. The net value is the lowest compared to other assessed countries, followed by Malaysia. The net CO_{2eq} emission in Russian Federation, Japan, Czech Republic, Germany, US (East), UK, Finland and France are higher, and the AD is environmentally preferable than incineration. However, the relationship is rather complicated as the net CO_{2eq} emission and electricity production mix are affecting each other. A more comprehensive study including the WtE technology level of a country, cost, product demand, using the energy as heat and a more details transporting information will be conducted in the future.

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