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How should greenhouse gas emissions be taken into account in the decision making of municipal solid waste management procurements? A case study of the South Karelia region, Finland

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ABSTRACT

The ongoing trend in the public sector is to make more sustainable procurements by taking into account the impacts throughout the entire life cycle of the procurement. Despite the trend, the only deciding factor can still be the total costs. This article answers the question of how greenhouse gas (GHG) emissions should be taken into account in municipal solid waste (MSW) management when selecting an incineration plant for source separated mixed MSW. The aim is to guide the decision making of MSW management towards more environmentally friendly procurements.

The study was carried out by calculating the global warming potentials (GWPs) and costs of mixed MSW management by using the waste composition from a case area in Finland. Scenarios of landfilling and combustion in three actual waste incineration plants were used to recognise the main processes that affect the results. GWP results show that the combustion of mixed MSW is a better alternative than landfilling the waste. The GHG results from combustion are greatly affected by emissions from the combustion and substituted energy production. The significance of collection and transportation is higher from the costs' perspective than from the point of view of GHG emissions. The main costs, in addition to collection and transportation costs, result from the energy utilization or landfilling of mixed MSW.

When tenders are invited for the incineration location of mixed MSW, the main focus should be: What are the annual electricity and heat recovery efficiencies and which are the substituted fuels in the area? In addition, in the case of a fluidized bed combustor it is crucial to know the combusted share of mixed MSW after preparing solid recovered fuel (SRF) and the treatment of rejects. The environmental criteria for the waste incineration plant procurements should be made in order to obtain clear instructions for the procurement units. The results can also be utilized more widely. The substituted fuels in the area and the effect of the plant location on the utilization of the produced energy can already be identified when planning an appropriate site for the waste incineration plant.

1. Introduction

More than 30% of municipal waste was landfilled in the European Union (EU-27) in the year 2012. Landfilling rates decreased from 63% to 34% between the years 1995 and 2012. At the same time in the Nordic Countries of Sweden, Denmark, and Norway landfilling rates have fallen below 5% and incineration rates now account for more than 50%. (Eurostat, 2014.) Landfill bans on combustible/biodegradable waste have been introduced in these countries (Fischer et al., 2012). According to the landfill directive of the EU, by 2016 the biodegradable municipal waste ending up in landfills must be reduced to 35% of the total amount of biodegradable municipal waste produced in 1994 (1999/31/EC). The EU is also committed to reducing greenhouse gases (GHGs) by at least 20% by 2020 (Ministry of the Environment, 2011) and at least 40% by 2030 (European Commission, 2014) compared to the 1990 level.

In 2012, in Finland the landfilling rate of municipal solid waste (MSW) was 33% (0.90 Mt) and the energy utilization rate of MSW was 34% (0.93 Mt) (Statistics Finland, 2013b). The waste management sector produced approximately 3% (2.1 Mt CO_2-eq) of the GHG emissions in Finland in 2012. Emissions from landfills contribute over 84% of the total GHG emissions from the waste management sector. The total GHG emissions have decreased 48% since 1990. The main part of this reduction results from the decrease in the landfilling of waste in Finland. At the same time,

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incineration of MSW has become more common in past few years. However, the GHG emissions from waste incineration, collection, and transportation are allocated to the emissions of the energy sector. (Statistics Finland, 2014.) In 2014, eight incineration plants used only waste as a fuel, and more waste incineration plants are under construction (Finnish Solid Waste Association, 2014).

Behind the changes in the Finnish waste management sector are e.g. the forthcoming landfill ban and different targets. The Government of Finland (2013a) has accepted a new landfill decree where the maximum allowed proportion of total organic carbon (TOC) or loss on ignition (LOI) for the landfilled non-hazardous waste will be 10% at MSW landfills in 2016. It is believed that this will reduce emissions from the landfills even more. The ban is estimated to affect approximately 2 Mt of waste which is still landfilled. One of the fractions with a share of about 50% is the mixed MSW which exceed the limit. An alternative treatment is going to be waste incineration, and consequently, e.g. less CH_4 is produced from the landfills. (Wahlström et al., 2012.) Finland's obligation for those sectors not covered by the emissions trading scheme (non-ETS sectors such as waste) is to reduce by 2020 the GHG emissions by 16% from the 2005 level. In addition, the Government of Finland adopted, in 2009, a target of reducing by 2050 Finland's GHG emissions by at least 80% from the 1990 level. (Ministry of the Environment, 2011.)

The EU directive on public procurement (2014/24/EU) includes an option to take account of environmental factors and also the life-cycle costs. The public sector is constantly being encouraged to make more sustainable procurements, where the whole impact of the procurement's life cycle is taken into account. The Government of Finland (2013b) has decreed a decision, in principle, where the procurement unit of the state is obligated to take environment aspects into account when planning procurements by 2015, at the latest. This principle is still a recommendation for other procurement units such as waste management companies owned by municipalities. Waste management companies send out invitations to tender and buy the main proportion of services from private companies by using public procurement procedures. (The Government of Finland, 2013b.) Nowadays, the waste management companies in Finland are much more accustomed to taking into account waste collection and transportation emissions when invited to tender. The EU has already made binding criteria for road transport vehicles and services (2009/33/EC), and e.g. the EU and Sweden have also made their own voluntary criteria for transportation (European Commission, 2012; The Swedish Environmental Management Council, 2009). Despite the greener transportations, the only deciding factor can still be the total costs when e.g. inviting tenders for the incineration location of mixed MSW.

A comparison of landfilling and incineration of MSW from the point of view of GHG emissions has been done in many studies (e.g. Kaazke et al., 2013; Monni, 2010; Ragoßnig et al., 2009; Wittmaier et al., 2009). Landfilling has been the prevailing waste management solution or the way to handle waste before, and therefore, it has been modelled for comparative purposes. All of these studies are in favour of incineration. Moreover, significant factors when calculating total global warming potentials (GWPs) are mentioned, like energy recovery efficiency of the incineration plant and substituted fuels (e.g. Myllymaa et al., 2008b; Vainikka et al., 2012). Myllymaa et al. (2008b) has also mentioned that the location of an incineration plant affects the annual energy efficiency and substituted heat is calculated based on the heat production in the area. Thus, the composition of fuels used to produce the substituted heat energy ranges widely between different studies (e.g. Astrup et al., 2009; Monni, 2010; Myllymaa et al., 2008b; Wittmaier et al., 2009). These details show that there are significant factors that affect the GWP results. At the same time, waste incineration plants have an equal right to give an offer for the combustion of mixed MSW.

The aim of the study is to calculate the GWPs and the costs of mixed MSW management by using the waste composition from a rural area in the South Karelia region in Finland. The mixed waste is source separated which means that inhabitants are instructed to separately sort fractions of biowaste, glass, metals, cardboard, and paper so that the mixed MSW is the leftover fraction that is directed to the landfill or incineration. Still in 2012, landfilling was the way to handle the mixed MSW, and thus both landfilling and incineration of mixed MSW in the different locations were studied. The case study included the actual locations in Finland and the case is based on an actual invitation to tender situation in 2012; with the exception of one of the incineration plants which was still under construction in 2014. One of the incineration plants is the same as studied by Monni (2010). It is noteworthy that Monni (2010) did not compare the GWP results to other plants, the costs were not included in the study and the used waste composition was from a different area. Horttanainen et al. (2013) has noted that the composition of mixed MSW also varies in different areas inside Finland. This indicates the need to conduct regional GHG emission studies where the specific waste composition is taken into account.

The aim of this study is to recognise the main processes that affect the results and to find out how the GHG emissions should be taken into account in the decision making of MSW management procurements. The goal is to guide the decision making of MSW management towards more environmentally friendly procurements. Transport costs have traditionally been considered as one of the most deciding factors when making waste management procurements. Therefore, an investigation was also conducted to find out what is the contribution of waste transport emissions to the total GHG emissions, and should the waste transportation also be in focus in procurements from the environmental point of view.

2. Materials and methods

Life cycle assessment (LCA) is a tool to evaluate the potential environmental impacts related to waste management options throughout a life cycle (Ekvall et al., 2007; SFS-EN ISO 14044, 2006). LCA enables taking into account the environmental benefits that can be obtained through waste management processes, e.g. waste incineration where energy recovery reduces the need for other energy sources, and material from recycling processes replaces the production of virgin material. The LCA tool can be used to compare different options in waste management. (Ekvall et al., 2007.) This makes it possible to use the information developed in an LCA study as a part of a decision-making process (SFS-EN ISO 14044, 2006).

The life cycle of the mixed MSW begins from the moment the waste is delivered to the regional collection point and continues until the waste is utilized or landfilled. The unit processes from the mixed MSW collection to the utilization or landfilling of the waste were taken into account, including the production of auxiliary substances, the treatment of the end products of combustion, the recycling of metals, and substitutions. The functional unit used was the amount of mixed MSW in one year from the study area. The functional unit is used in an LCA study as a reference unit (SFS-EN ISO 14044, 2006). The GHG emissions investigated in this study were CO_2, CH_4 and N_2O. The GWP was evaluated through a 100-year time span. The GWP of the system was assessed in compliance with the ISO standards 14040 (SFS-EN ISO 14040, 2006) and 14044 (SFS-EN ISO 14044, 2006). The GaBi 6.0 life cycle modelling software and a methodology CML 2001 – November 2010 for impact assessment were used in the study (GaBi).

2.1. Description of the study area

The study area is a part of the rural area of the South Karelia region in Finland consisting of the following municipalities: Parikkala, Rautjärvi, Ruokolahti, Savitaipale, Luumäki and Taipalsaari (see Fig. 1). The surface area of these municipalities is 4695 km^2 (National Land Survey of Finland, 2012). The inhabitants from 3792 permanent dwellings and 13,400 holiday homes take their garbage bag to the regional collection points in this area. There are 141 regional collection points used all year-round and eight collection points are used only in the summertime. (Etelä-Karjalan Jätehuolto Oy.) The annual amount of mixed MSW from these collection points was included in the study. The waste amount was calculated by using the amount and size (from 600 l to 8 m^3) of waste bins at the collection points, the emptying schedules, and an assumption of MSW density (50 kg/m^3) (Etelä-Karjalan Jätehuolto Oy). Hence the total waste amount is about 3100 t_{MSW}/a.

The mixed MSW is transported from the regional collection points to the waste management company in the city of Lappeenranta. The municipalities of South Karelia own the company that is responsible for the waste management. The company calls for tenders for the collection, transportation, and combustion of the mixed MSW. The landfilling and the reloading of the mixed MSW takes place at the company in Lappeenranta. (Etelä-Karjalan Jätehuolto Oy.)

2.2. Description of scenarios

Landfilling has been the only way to treat the mixed MSW in the South Karelia region. In 2012, the waste management company invited tenders for the combustion of the mixed MSW. It was decided that the mixed MSW was to be transported and combusted in the grate furnace in Riihimäki, however, this is not the closest incineration plant. The decision was made based on the total cost of transportation and treatment. Transport of the mixed MSW started in the beginning of 2013. The change has been made step by step so that all the mixed MSW will be combusted in 2015. (Etelä-Karjalan Jätehuolto Oy, 2013.)

Two main scenarios (see Fig. 2) were selected for the study:

- Scenario 0: The mixed MSW is collected and transported to landfill in Lappeenranta. This was still the situation in 2012.
- Scenario 1: The mixed MSW is collected and transported to Lappeenranta where the waste is reloaded. Scenario 1 was divided into three sub-scenarios in which the reloaded mixed MSW is:
  - (1.1) Transported to Riihimäki (220 km) and combusted in the grate furnace. This will be the actual situation by 2015, at the latest.
  - (1.2) Transported to the nearest waste incineration plant in Kotka (120 km) and combusted in the grate furnace.
  - (1.3) Transported to a waste incineration plant in Leppävirta (210 km) that is now under construction in 2014, and pretreated, and combusted in the fluidized bed boiler.

2.3. Collection and transportation

The data used to calculate the emissions linked to collection and transportation is presented in Table 1. The mixed MSW collection transportations are the same in all Scenarios 0–1. The average distances to every regional collection point were calculated based on the addresses of the collection points in the Transport Control System (Ecomond Oy, 2013). A total collection drive of about 37,800 km/a was then derived with the help of the emptying schedule (Etelä-Karjalan Jätehuolto Oy). The weighted average distance from previous address to the regional collection point was calculated to be from 4 km to 7 km, depending on the area. Idling

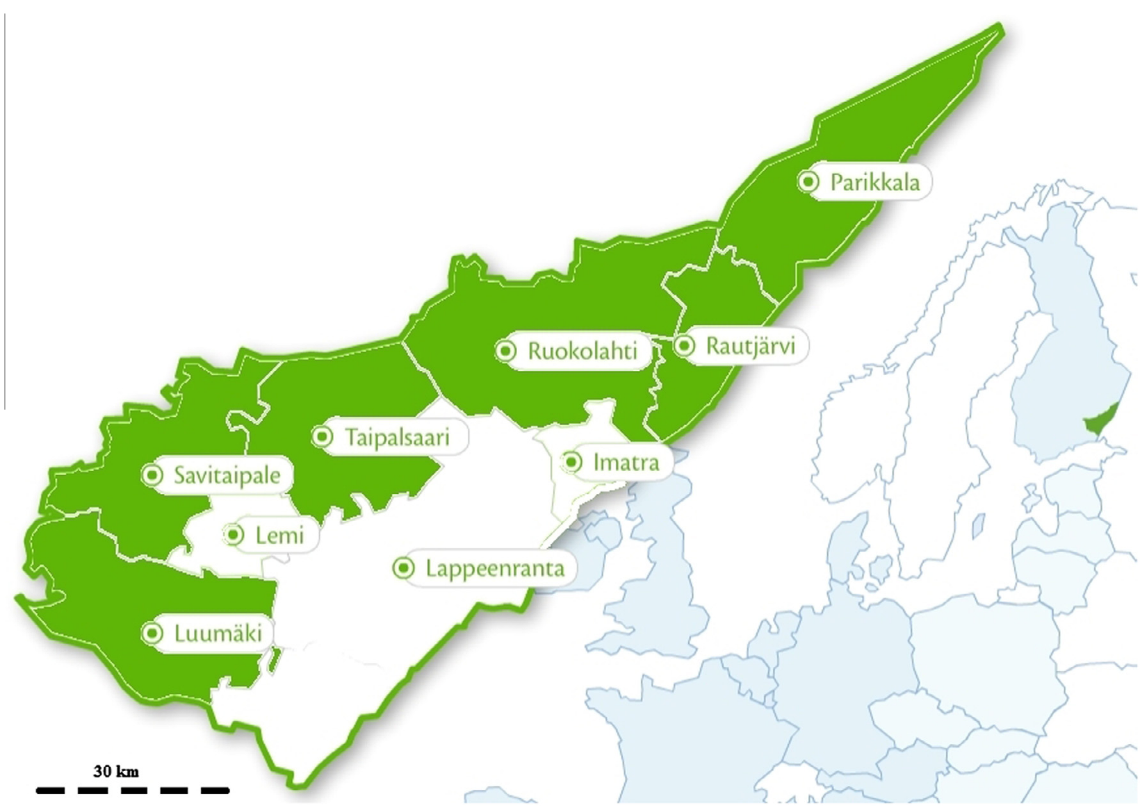

Fig. 1. The study area in the South Karelia region of Finland (South Karelia).

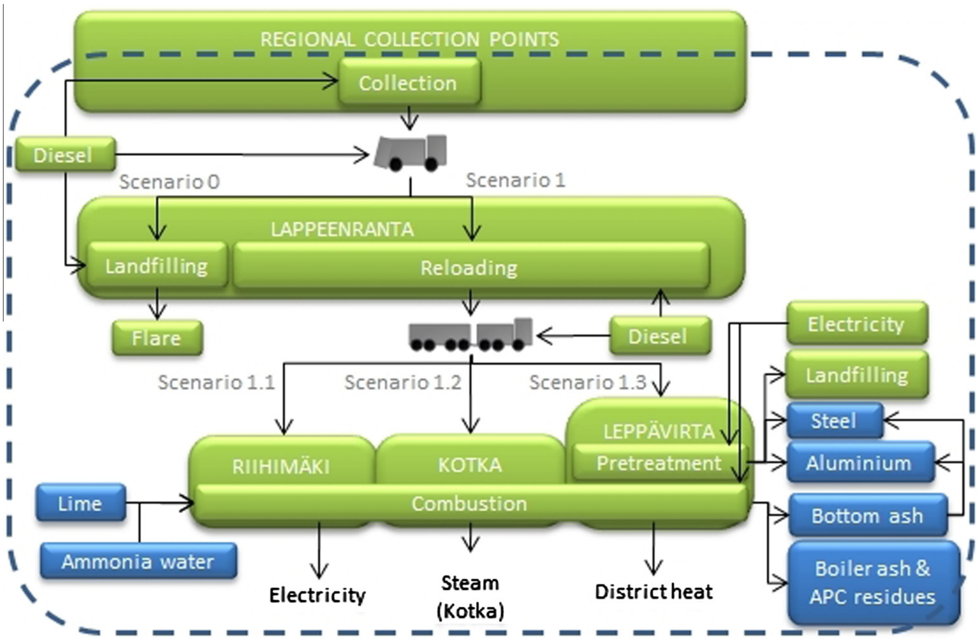

Fig. 2. Description of the scenarios.

Table 1
The data used to calculate the emissions linked to collection and transportation.

	Unit	Collection area						Reference
		Parikkala	Rautjärvi	Ruokolahti	Savitaipale	Luumäki	Taipalsaari	
Regional collection points, used year-round	Pieces	26	11	38	27	34	5	Etelä-Karjalan Jätehuolto Oy
Regional collection points, used summertime	Pieces	–	–	7	–	1	–	Etelä-Karjalan Jätehuolto Oy
Collection drive	km/a	5581	3327	12,081	7448	8408	930	Calculated
The weighted average distance	km/regional collection point	6	5	7	6	5	4	Calculated
Round trips between collection areas and the waste management company	km	191	158	101[a]	103	107	60	Calculated
		Collection and transportation						
Waste collection & round trips		9 t garbage truck, a half load						
Other transportations		Loads and distances resemble the actual situation						
Total idling time during the collection (bin size)	s	60 (600–660 l)			300 (4–8 m^3)			Etelä-Karjalan Jätehuolto Oy
Idling (bin size)	% of the stopping time	33 (600–660 l)	25 (4–8 m^3)		67 (600–660 l)	75 (4–8 m^3)		Teerioja (2009)
Diesel consumption during the idling	l/h	3			5			
		e.g. the driver is retrieving a bin			e.g. the waste bin is emptied and the waste is pressed			Teerioja (2009)
Diesel consumptions and exhaust emissions from the road transportations								Lipasto (2012)
Diesel production								GaBi

[a] Used partly also for Taipalsaari because part of the waste is transported through Ruokolahti.

during the collection was taken into account. The differences in transportations results from when the waste is transported forward from Lappeenranta in Scenarios 1.1–1.3.

2.4. Mixed MSW composition

The composition of the source separated mixed MSW in the South Karelia region of Finland was studied at the end of 2010 (October–December) by taking 13 samples from waste loads collected from different parts of the collection region. The average composition was used of three samples collected from the study area, the rural area of the South Karelia. (Teirasvuo, 2011a.) In April 2011, the mixed MSW was studied more specifically by taking two samples from waste loads collected from the urban area of the city of Lappeenranta, situated in the South Karelia region (Teirasvuo, 2011b). The 600 l samples were manually separated into the different fractions (Horttainen et al., 2013; Teirasvuo, 2011a,b). Fractions and other properties of the mixed MSW which are used in calculations are presented in Table 2. The non-recyclable combustible waste was separated as renewable (approx. 43 wt.%) and non-renewable (approx. 57 wt.%) based on the second sampling. The calculated lower heating value of the mixed MSW as received (LHVar) from the case area was 15.2 MJ/kg_{MSW}, the total degradable organic carbon (DOC) content was 15.1% of wet waste and the $CO_{2,fossil}$ was 648 kg/t_{MSW}. This means 43 t_{CO2}/TJ.

Table 2
The properties which are used in the calculations of the source separated mixed MSW from South Karelia, Finland.

	Composition of the MSW (wt.%)	LHVar (MJ/kg)	DOC content (% of wet waste)	Dry matter content (wt.%)	Total C content (% of dry weight)	Fossil C fraction (% of total C)
Biowaste	27.1	4.2	16			0
Landfill waste[a]	11.7	27.9	–	89	3	100
Recyclable carton and paperboard	6.0	15.8	40			0
Recyclable paper	4.5	12.3	40			0
Glass	2.4	–	–	100	–	–
Metals	4.0	–	–	100	–	–
Recyclable plastics[b]	0.2	20.7	–	98	75	100
Non-recyclable plastics	21.5	28.8	–	82	75	100
Non-recyclable combustible waste, renewable[c]	6.2	15.5	40			0
Non-recyclable combustible waste, non-renewable[d]	8.3	19.1	40	95	50	100
Other combustible waste[e]	4.9	10.7	16	63	70	10
Dangerous waste	0.7	–	–	100	–	–
Electric and electronic waste	2.4	–	–	100	–	–
Reference	Teirasvuo (2011a)	Teirasvuo (2011b)	Petäjä (2007)	Teirasvuo (2011b)	IPPC (2006)	IPPC (2006)

DOC: degradable organic carbon.
[a] Aluminium containing packages, non-combustible waste, fines, ceramics, non-recyclable glass and dust bags.
[b] Bottles suitable to existing packaging recycling.
[c] Wood, renewable textiles, non-recyclable paper, carton and paperboard.
[d] Non-renewable textiles and other non-renewable materials.
[e] Diapers and sanitary towels, packaging containing food and bones.

2.5. Landfilling of mixed MSW

In Scenario 0, the mixed MSW was directed to a landfill in Lappeenranta. The CH_4 generation potential of mixed MSW was calculated by using the equation of

$$L_o = \mathrm{DOC} \cdot \mathrm{DOC}_f \cdot \mathrm{MCF} \cdot F \cdot 16/12 \quad (1)$$

where L_o is CH_4 generation potential [$\mathrm{Gg_{CH4}/Gg_{waste}}$], DOC is the already mentioned fraction of degradable organic carbon in the waste [$\mathrm{Gg_C/Gg_{waste}}$], DOC_f is the fraction of DOC that decomposes [wt.%], MCF is the methane correction factor [−], F is the fraction of CH_4 in generated landfill gas [%] and 16/12 is the molecular weight ratio CH_4/C [−] (IPPC, 2006). In the equation, the recommended default value of 50 wt.% was used for DOC_f (IPPC, 2006; Petäjä, 2007). The MCF for aerobic managed solid waste landfill sites is 1.0 and F is about 50% (Etelä-Karjalan Jätehuolto Oy, 2013; IPPC, 2006; Petäjä, 2007).

The landfill gas collection efficiency typically ranges from 50% to 95%. A default efficiency of 75%, recommended by The United States Environmental Protection Agency, was applied in this study. (EPA, 2008.) According to Chanton et al. (2009) the fraction of methane oxidized on transit across the soil covers is 36%. Landfill compactor's diesel consumption and exhaust gases were included in the study. According to Niskanen et al. (2013) the treatment efficiency for CH_4 by flaring is 99%.

2.6. Combustion of mixed MSW

In Scenario 1, the mixed MSW was reloaded into a trailer in Lappeenranta and transported to a waste incineration plant with a load of 33 t (Etelä-Karjalan Jätehuolto Oy). The GHG emissions from the loading and transportation were included in the study. The data, used in the calculations in Scenarios 1.1–1.3, is presented in Table 3.

Table 3
The data used to calculate the emissions linked to the combustion Scenarios 1.1–1.3.

	Unit	Scenario 1.1	Scenario 1.2	Scenario 1.3	References
$CaO/Ca(OH)_2$, consumption	kg/t_{MSW}	5.1	5.3	5 (4–18)	Kotkan Energia Oy (2011), Mickos (2011), Monni (2010), ÅF-Consult Oy (2012)
Ammonia water, consumption	kg/t_{MSW}	4.0	4.2	4.7	Kotkan Energia Oy (2011), Kylmälä (2011), Monni (2010), ÅF-Consult Oy (2012)
Plant, total annual energy efficiency	%	64	68	66	Ekokem Oy Ab (2014), Kotkan Energia Oy (2013), Markkanen (2013), ÅF-Consult Oy, (2012)
Plant, annual electricity efficiency	%	12	10	26	Ekokem Oy Ab (2014), Kotkan Energia Oy (2013), Markkanen (2013), ÅF-Consult Oy, (2012)
Plant, own need of electricity	MJ/kg	0.29	0.29	0.34	Myllymaa et al. (2008a)
Share of bottom ash	% of MSW	16	17	1	Markkanen (2013), Monni (2010), ÅF-Consult Oy (2012)
Share of boiler ash	% of MSW	1	1	4	Kaartinen et al. (2007), Markkanen (2013), Monni (2010), ÅF-Consult Oy (2012)
Share of APC residues	% of MSW	2	2	9	Kaartinen et al. (2007), Markkanen (2013), Monni (2010), ÅF-Consult Oy (2012)
Reprocessing of steel	kg CO_2-eq./t		508 (367–1286)		Daamgaard et al. (2009), Kuusiola (2010)
Reprocessing of aluminium	kg CO_2-eq./t		505 (421–1074)		Daamgaard et al. (2009), Kuusiola (2010)
Virgin production of steel	kg CO_2-eq./t		2103 (1612–2816)		Daamgaard et al. (2009), Kuusiola (2010)
Virgin production of aluminium	kg CO_2-eq./t		9852 (6632–20,737)		Daamgaard et al. (2009), Kuusiola (2010)

APC: Air Pollution Control.

Pretreatment of the mixed MSW to produce solid recovered fuel (SRF) was only used in Scenario 1.3 where the fluidized bed boiler is in use. According to Räsänen (2013) the electricity consumption of pretreatment is about 14 kW h/t_{MSW}. According to ÅF-Consult Oy (2012) the share of reject is 5% of the mixed MSW and the share of metals 2% of the mixed MSW. The separated reject is reported to be mainly non-combustible and the plan is to direct the reject to landfill (ÅF-Consult Oy, 2012). Because of this, the reject was assumed to be inert waste which was landfilled by using the GaBi process. Separated reject and metals have been taken into account in LHVar of the SRF (16.3 MJ/kg_{SRF}).

GHG emissions from the productions and transports of CaO or $Ca(OH)_2$ and ammonia water (24.5%), which are needed in the flue gas treatment of the incineration plants, were also included in the study. Production emissions of these substances were derived from GaBi.

The total annual energy efficiency is the sum of annual electricity and heat efficiencies, which include only the part of heat which is utilized. This means that the annual energy efficiencies are connected to how much of the produced heat is possible to utilize in the area year-round without cooling, e.g. in the summer. For example, the total energy efficiency of Scenario 1.3 would be about 85–88% without this cooling. (ÅF-Consult Oy, 2012.) The total annual energy efficiencies of the waste incineration plants are 64–68% in the case study (see Table 3). This means that the part of heat which is not utilized was not included in this study. The difference between the plants can be seen in the annual electricity efficiencies, Scenario 1.3 can be seen to have significantly greater efficiency. According to Fruergaard et al. (2009) the average electricity data can be used when quantifying the environmental load of a waste management system. The substituted electricity production was then assumed to be the electricity grid mix in Finland. The avoided emissions were derived from GaBi databases in 2011. The substituted heat production depends on the area. According to Markkanen (2011) and Ekokem Oy Ab in Scenarios 1.1 and 1.2, it can be assumed that the produced district heat replaces thermal energy from natural gas and in Scenario 1.2, produced steam replaces process steam from natural gas. According to the local district heat producers (Ursin, 2013; Varkauden Aluelämpö Oy, 2013) in Scenario 1.3, the produced district heat replaces biofuels (72%), plastics waste (19%), heavy fuel oil (7%) and coal (2%). The data on avoided emissions was derived from GaBi and from Statistics Finland (2013a).

The share of end products varies depending on the boiler technology (see Table 3). The bottom ash is treated in the same area of the incineration plant, except in Scenario 1.2 where the transportation emissions were included. According to Monni (2010) the diesel consumption for the bottom ash treatment is 0.5 l/t_{ash}. Exhaust emissions of the treatment were derived from LIPASTO (2012). According to Meriluoto (2013) 5–10% of the bottom ash is unexploitable. The unexploitable share was assumed to be 5%, and assumed to be landfilled. The treated bottom ash replaces gravel based on the volumes 1:1 (Ekokem Oy Ab; Regional State Administrative Agency for Southern Finland, 2011). A moisture content of 20% was used for the bottom ash (Kaartinen et al., 2010). The emissions avoided by processing the gravel were derived from GaBi.

The boiler ash and Air Pollution Control (APC) residues are transported in Scenarios 1.1 and 1.2 before the fractions are solidified with cement (Takainen, 2013; ÅF-Consult Oy, 2012). The cement was transported to the treatment area and a consumption of 35 wt.% was used for the APC-residues and 7 wt.% for the boiler ash (Monni, 2010). According to Koivunen (2007) the electricity consumption of the solidification is 17.5 kW h/t (15–20 kW h/t). The cement production, the average electricity production in Finland, and landfilling of the inert fraction were calculated based on values provided by GaBi.

In all the scenarios, 50% recovery of the metals was applied. Metals were recovered from the preparing of SRF in Scenario 1.3 and from the bottom ashes. Metals in the mixed MSW were assumed to be mainly (80%) steel. Steel is used for example in tins, glass jar lids and spray cans (Mepak-Kierrätys Oy, 2012). The remaining part (20%) was assumed to be aluminium. Metals were loaded and transported to pretreatment. According to Daamgaard et al. (2009) diesel consumption of pretreatment is 2.5 l/t_{metals} and electricity consumption is 50 kW h/t_{metals}. According to Mepak-Kierrätys Oy (2012) and Moliis et al. (2012) the steel scrap is transported, after the pretreatment, to Germany. The emissions from the sea transport were derived from GaBi. According of Moliis et al. (2012) the aluminium is pretreated and reprocessed in Finland. The reprocessing of the steel and aluminium scraps and substituted virgin productions of both the metals were included in the study.

2.7. Costs of mixed MSW management

The costs of the mixed MSW from the regional collection points to the landfill or to the combustion with the treatment of the end products were calculated from the point of view of the waste management company. According to the company 33% of the waste bins are repaired every year because the condition of the bins deteriorates. Conveyance of these repaired bins has also been taken into account in the cost calculations. According to the company, snow removal and cleaning costs per the regional collection point were assumed to be same in different municipalities. The lease of the land depends on the collection points, e.g. there is no lease if the collection point is in the area of municipalities or the state. Collection and transportation cost to Lappeenranta include the cost that the waste management company pays to a transport company when the bins are emptied based on the emptying schedule. (Etelä-Karjalan Jätehuolto Oy.)

Costs were calculated based on the information from the waste management company. In Scenario 0, where the waste is landfilled, costs resulting from e.g. groundwork and after-care of the landfill, staff, outsourcing services, development, investment and share of land acquisition, and infrastructure were included as the landfill costs. In Scenario 1, where the waste was combusted, cost resulting from investment costs of transfer depot, staff, loader and consumption of electrical energy were included as reloading costs. The transportation cost of the mixed MSW to the incineration plant was obtained in the unit of €/km. Combustion and treatment of the end products and also waste management's staff, development, investments and share of infrastructure costs were included as the energy utilization costs. The cost of combustion was derived in Scenarios 1.1 and 1.2 based on the invitation to tender 2012. (Etelä-Karjalan Jätehuolto Oy.) In Scenario 1.3, the combustion cost is not known yet because the plant is still under construction. Due to this, the same combustion cost was used as in Scenario 1.1. The sensitivity of the choice of combustion cost was also checked in Scenario 1.3 by using the same combustion cost as in Scenario 1.2. The same treatment cost of the end products was used in all Scenarios 1.1–1.3 based on the value from Riihimäki (Etelä-Karjalan Jätehuolto Oy).

3. Results and discussions

3.1. Global warming potentials of mixed MSW management

The GWPs for the mixed MSW in the South Karelia region of Finland are presented in Fig. 3. According to the GWPs Scenario

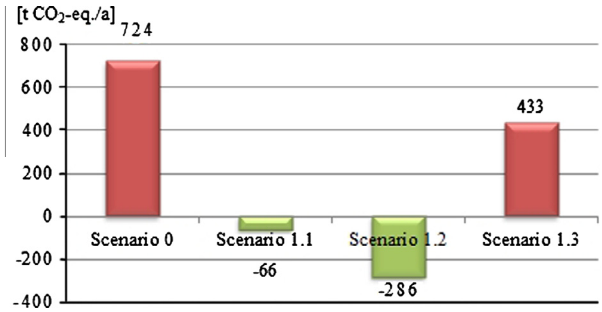

Fig. 3. GWPs for mixed MSW management in the South Karelia region of Finland.

1, where mixed MSW is incinerated, this is a better alternative than Scenario 0 where mixed MSW is landfilled. Produced emissions and avoided emissions are presented in detail in Table 4.

In Scenario 0, the main impact is the generated CH_4 emission from the mixed MSW. The CH_4 collection to the flare was calculated by applying a gas collection efficiency of 75% but the range of efficiency is wide (50–95%). The GWP result validates the decision to restrict the landfilling of organic waste fractions in EU and in Finland (1999/31/EC; The Government of Finland, 2013a).

In Scenarios 1.1–1.3, the main impacts are from the emissions from the combustion and the avoided emissions from electricity and heat production, which are all linked to the composition of mixed MSW. The lowest GWP is in Scenario 1.2 mainly because of the highest total annual efficiency. At the same time, the highest annual electricity efficiency is in Scenario 1.3, but the result of this scenario is weakened by the use of mainly biofuels as the fuel of substituted heat, which is the estimated situation in that area. Therefore, the substituted fuels used strongly affect the final results. The results also show that the emissions from collection and transportations of the mixed MSW are fairly minor.

The sensitivity of the mixed MSW composition in the results was further analysed because e.g. the LHVar (15.2 MJ/kg_{MSW}) and $CO_{2,fossil}$ (648 kg/t_{MSW}) were calculated based on the waste composition which varies in different areas in Finland (Horttanainen et al., 2013). According to Statistics Finland (2013a) the LHVar of mixed MSW is 10.0 MJ/kg_{MSW} and $CO_{2,fossil}$ is 400 kg/t_{MSW}. The impact of these values is seen in decreased emissions from the combustion but also avoided emissions are decreased when less energy is produced. Overall, the total GWP decreases 68% in Scenario 1.1 and 42% in Scenario 1.3, whereas the GWP increases 9% in Scenario 1.2 when values from Statistics Finland (2013a) were used to estimate the difference. Despite the changes in values of the LHVar and $CO_{2,fossil}$, the order of the scenarios is the same as presented before (see Fig. 3).

The sensitivity of the choice of fuel for substituted heat production was also calculated by using natural gas in Scenario 1.3, instead of using mainly biofuels. In this case, the total GWP is −262 t CO_2-eq./a which is similar to Scenario 1.2. This result indicates that the substituted fuels have a considerable effect on the results.

Table 4
Produced emissions and avoided emissions from different processes.

	Emissions (kg CO_2-eq./a)				Avoided emissions (kg CO_2-eq./a)			
	Scenario 0	Scenario 1.1	Scenario 1.2	Scenario 1.3	Scenario 0	Scenario 1.1	Scenario 1.2	Scenario 1.3
Collection and transportation of the mixed MSW to Lappeenranta	55,366	55,366	55,366	55,366				
Landfilling	CH_4 generation				CH_4 collection to flare			
	3,950,087	-	-	-	- 2,962,565	-	-	-
	Diesel consumption of landfill compactor				Oxidation of CH_4			
	6926	-	-	-	- 355,508	-	-	-
	CH_4 leaks from flare							
	29,626	-	-	-				
Combustion	Reloading and transportation of the mixed MSW to the plant				Substituted electricity production			
	-	31,882	19,172	30,727	-	- 479,391	- 385,111	- 1,121,141
	Pretreatment and landfilling of the reject				Substituted heat production			
	-	-	-	17,184	-	- 1,572,219	- 1,875,202	- 512,892
	Transportation and production of $CaO/Ca(OH)_2$				Substituted gravel processing do to utilization of bottom ash			
	-	19,535	20,978	14,083	-	- 1382	- 1508	- 131
	Transportation and production of ammonia water				Substituted steel production			
	-	8680	9235	9451	-	- 105,598	- 105,598	- 105,598
	Combustion of waste				Substituted aluminium production			
	-	2,034,882	2,034,882	2,031,315	-	- 123,675	-123,675	-123,675
	Transportation and treatment of bottom ash							
	-	1064	2080	88				
	Transportation and treatment of boiler ash and APC residues							
	-	26,025	24,226	99,369				
	Transportation, pretreatment and reprocessing of steel							
	-	31,871	32,049	32,333				
	Transportation, pretreatment and reprocessing of aluminium							
	-	6721	6719	6774				
Total	4,042,005	2,216,024	2,204,707	2,296,688	- 3,318,073	- 2,282,265	- 2,491,093	- 1,863,437

The sensitivity of the share of SRF produced was also examined. According to ÅF-Consult Oy (2012) 93% of the mixed MSW was assumed to be incinerated as SRF after the pretreatment in Scenario 1.3. According to literature, the share is more likely to be 60% in the range of 58–68% (Consonni et al., 2005a; Makkonen, 2002; Myllymaa et al., 2008b; Siipola, 2009; Thiel and Thomé-Kozmiensky, 2010). Consonni et al. (2005a) has introduced an educated guess of shares for different waste fractions removed in the RDF production: 6 wt.% for paper and cardboard, 6 wt.% for wood, 5 wt.% for plastics, 95 wt.% for glass and inert material, 96 wt.% for metals, 78 wt.% for organic fraction and 50 wt.% for fines. Given these values and the composition of the mixed MSW from the South Karelia region of Finland, 61% of the mixed MSW was calculated to be incinerated as SRF. The LHVar of the SRF will then be 19.8 MJ/kg.

The sensitivity of the SRF reject treatment and the share of recovered metals were examined in three ways:

(1) The reject is landfilled by using a calculated CH_4 generation potential of the reject and at the same time the recovery of metals is 96 wt.%.
(2) The reject (8.8 MJ/kg) is transported to Riihimäki and utilized as energy in the grate furnace because of the forthcoming landfill ban of organic waste and the recovery of metals is 96 wt.%.
(3) The reject is treated the same way as in the second manner but the recovery of metals is assumed to be 50 wt.%, instead of 96 wt.%.

The total GWP in Scenario 1.3 is 569 t CO_2-eq./a when the reject is landfilled. The GWP is increased mainly because of the generated CH_4 emission from the landfill and the decreased substituted electricity and heat, but, at the same time, the more affective metal recovery (96 wt.% instead of 50 wt.%) increased the avoided emissions. The total GWP in Scenario 1.3 is 141 t CO_2-eq./a when the removed fraction is combusted in the grate furnace. If the recovery of metals is 50 wt.%, instead of 96 wt.%, the total GWP is 318 t CO_2-eq./a. Results show that the reject should be utilized as energy and the total GWP decreases compared to the main Scenario 1.3 when part of the mixed MSW is treated in another incineration plant where the substituted heat is produced from natural gas instead of using mainly biofuels. In addition, the recovery of metals affects the results, although the share of metals is only approximately 4% in the mixed MSW.

3.2. Costs of mixed MSW management

The relative costs for mixed MSW management in the South Karelia region of Finland are presented in Fig. 4. According to the results, the most expensive existing way to treat mixed MSW is to direct the waste to a landfill, which is done in Scenario 0. The least costly existing way is Scenario 1.1, where the waste is transported to the waste incineration plant in Riihimäki, which is also the selected treatment location based on the call for tenders in 2012. The widest range in the total costs is achieved in Scenario 1.3 because the plant is still under construction. The maximum difference to Scenario 0 is 4% in Fig. 4. The maximum difference is only 1% when only the existing ways to treat the mixed MSW are examined. This means that smaller variation is achieved compared to the GWP results.

The main costs in the scenarios result from the treatment of mixed MSW and from the collection and transportation to Lappeenranta. The share of the energy utilization cost is 41–47%, the share of the landfilling cost is 58% and the share of collection and transportation to Lappeenranta is about 30% of the total costs. This means that the significance of collection and transportation is higher from the perspective of costs than from the point of view of the GWP.

The combined shares of reloading, transportation to the incineration plant, and energy utilization are compared more closely. The combined share is 57% of the total costs in Scenario 1.1 and 58% of the total costs in Scenario 1.2. The combined shares are similar to each other mainly because the transportation cost to the incineration plant is the smallest in Scenario 1.2, when the mixed MSW is transported to the nearest incineration plant, while the combustion cost is higher in Scenario 1.2 than in Scenario 1.1. The difference in the combined shares would have been more significant if both the transportation and combustion costs had been smaller/higher in Scenario 1.2 than in Scenario 1.1. If the combined shares mentioned are compared to the share of the landfilling cost (58%), the shares are similar to each other based on the results from the case area.

3.3. Comparison to other studies

The calculated GWPs were compared with other studies in Table 5. Comparing the results is challenging because the means of calculating the GWP of mixed MSW differ. Reimann (2012) has collected energy data from 314 European Waste-to-Energy

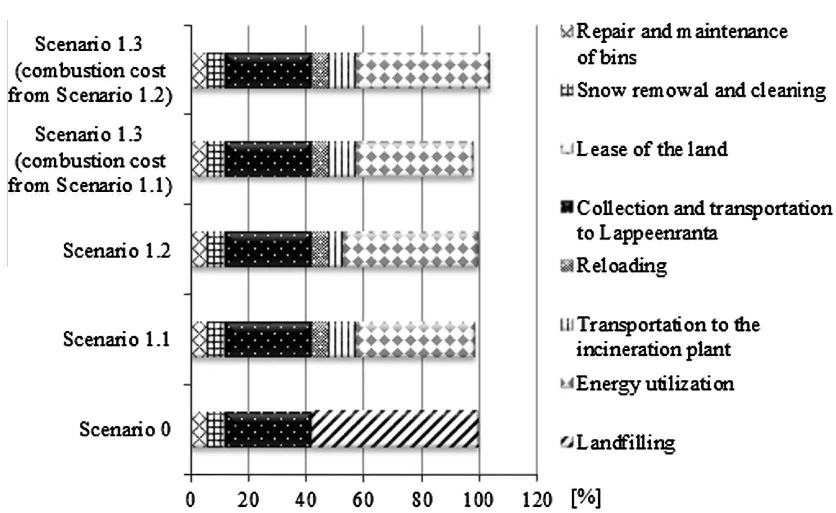

Fig. 4. The relative costs for mixed MSW management in the South Karelia region of Finland. The annual cost of Scenario 0 is 100% because the cost results consist of confidential data from the waste management company (Etelä-Karjalan Jätehuolto Oy).

Table 5
Comparison of the GWP results to other studies.

	Efficiency (electricity + utilized heat) (%)	Substituted heat	Substituted electricity	The total GWP (kg CO_2-eq./t_{ww})	Reference
Landfilling					
DE: landfill		–	Local power mix	399	Wittmaier et al. (2009)
FI: landfill		Natural gas 90%, heavy fuel oil 10%	–	283	Monni (2010)
Scenario 0, FI: landfill		–	–	231	This study
Energy utilization					
DE: waste incineration plant	39	Oil 85%, gas 15%	Local power mix	219	Wittmaier et al. (2009)
Scenario 1.3, FI: fluidized bed	66	Biofuels 72%, plastics waste 19%, heavy fuel oil 7%, coal 2%	Electricity mix in Finland	138	This study
FI: grate, urban area	36	Average production in Finland	Average production in Finland	About 0	Myllymaa et al. (2008b)
Scenario 1.1, FI: grate	64	Natural gas	Electricity mix in Finland	−21	This study
FI: grate	62	Natural gas 90%, heavy fuel oil 10%	–	−33	Monni (2010)
Scenario 1.2, FI: grate	68	Natural gas	Electricity mix in Finland	−91	This study
FI: grate	80 (estimation)	Natural gas 90%, heavy fuel oil 10%	Natural gas	−291	Monni (2010)
FI: fluidized bed, 60% SRF	75	Oil 64%, wood 36%	Coal	−350	Myllymaa et al. (2008b)
DK: grate	100 (assumption)	EU25	Energy mix for the Nordic countries, high share of hydro power	−358 to −47	Astrup et al. (2009)
FI: grate, industrial area	80	Wood 85%, natural gas 15%	Coal	−390	Myllymaa et al. (2008b)
FI: grate	80 (estimation)	Natural gas 90%, heavy fuel oil 10%	Coal	−412	Monni (2010)
FI: grate	68	Oil/natural gas	Natural gas	−451	Vainikka et al. (2012)
FI: fluidized bed, 56% SRF from household waste & 85% from commerce waste	68	Oil/natural gas	Natural gas	−498	Vainikka et al. (2012)
FI: grate, industrial area	80	Oil 56%, wood 32%, natural gas 12%	Coal	−590	Myllymaa et al. (2008b)
DK: grate	100 (assumption)	EU25	Central European energy mix, high share of coal	−967 to −282	Astrup et al. (2009)
FI: grate	68	Oil/natural gas	Coal	−1012	Vainikka et al. (2012)
FI: fluidized bed, 56% SRF from household waste & 85% from commerce waste	68	Oil/natural gas	Coal	−1305	Vainikka et al. (2012)

ww: wet waste.

plants. The difference in the average net caloric value of MSW and the average energy efficiency due to climate conditions between Northern Europe (FI, DK, NO, SE) and South-Western Europe (e.g. ES, IT and part of FR) is recognised based on the collected data (Reimann, 2012). Because of this difference, GWPs were compared mainly to studies conducted in Finland and other Northern European countries.

Landfilling results are not only linked e.g. to the composition of mixed MSW, to the estimate of the landfill gas collection efficiency, and to the fraction of methane oxidized on transit across the soil covers but also to the utilization of landfill gas. Monni (2010) and Wittmaier et al. (2009) assumed that the landfill gas is utilized, not flared, so avoided emissions are also calculated. According to the results, the mixed MSW should be directed to incineration in spite of the utilization of the landfill gas (Monni, 2010; Wittmaier et al., 2009).

Differencies in energy utilization results are connected mainly to the composition of mixed MSW and to the substituted energy production. The composition has an influence on the LHV of mixed MSW. LHV is usually 10–12 MJ/kg_{MSW} if the mixed MSW is directed to a grate furnace (Astrup et al., 2009; Consonni et al., 2005a; Monni, 2010; Myllymaa et al., 2008b; Vainikka et al., 2012; Wittmaier et al., 2009). In the case area, the LHV was calculated to be much higher (15.2 MJ/kg_{MSW}). This is because of the high share of plastics and small share of biowaste (Horttanainen et al., 2013). The LHV of the SRF is linked to the pretreatment used and the composition and share of SRF. For example, Myllymaa et al. (2008b) used an SRF share of 60% from mixed MSW, in the case of the fluidized bed, which affects for example, the energy content. Values of 14–17 MJ/kg_{SRF} are mentioned (Consonni et al., 2005a; Myllymaa et al., 2008b; Vainikka et al., 2012). The 16.3 MJ/kg_{SRF} used in Scenario 1.3 fits into this range. The composition of mixed MSW is also connected to the generation of fossil CO_2 emissions. Astrup et al. (2009) has demonstrated that the content of fossil carbon in the input waste is critical for the GHG emissions related to waste incineration. Values of 32–45 t_{CO2}/TJ are mentioned

(Consonni et al., 2005a,b; Monni, 2010; Myllymaa et al., 2008b; Vainikka et al., 2012; Wittmaier et al., 2009). The 43 t_{CO2}/TJ used fits into this range.

Differencies due to the choice of substituted energy production can clearly be seen in Table 5. The substituted heat is calculated based on the heat production in the case area, therefore the composition of the substituted fuels range widely. Difference is also evident in the substituted electricity production. If the substituted electricity is assumed to be produced with coal or with natural gas, the avoided emissions are increased as compared to the average electricity production or local power mix; because, for example, productions of hydro and nuclear electricity are also included in the electricity mix of Finland. Monni (2010) has omitted the avoided electricity production emissions because the produced electricity is calculated completely for the plant's own consumption.

The total annual energy efficiency also varies depending on where the plant is situated: urban area versus industrial area (Myllymaa et al., 2008b). Energy utilization is higher when there is an industrial plant which uses process steam year-round, in addition to the waste incineration plant (Myllymaa et al., 2008a). The energy utilization varies from 36% to about 80% (Monni, 2010; Myllymaa et al., 2008b; Wittmaier et al., 2009), but also an assumption of 100% is used in calculations (Astrup et al., 2009). Ragoßnig et al. (2009) have also recognised that the energy efficiency of waste-to-energy system is a crucial factor and underline the importance of choosing appropriate sites for waste incineration plants.

3.4. Discussion and conclusions

The only deciding factor was costs when the incineration location of mixed MSW was invited to tender in the case area. This means that all the mixed MSW is transported to Riihimäki and combusted in the waste incineration plant in 2015 (Scenario 1.1). The results of this study show that the choice would be different from the point of view of GHG emissions. According to the GWP results, the mixed MSW would be directed to Kotka for combustion in the waste incineration plant (Scenario 1.2). It is noteworthy that GHG emissions can be reduced by directing the mixed MSW to combustion instead of a landfill. This means that already the change in the treatment of mixed MSW decreases GHG emissions. When the aim is to decrease the GHG emissions more, the selection of the waste incineration location becomes a crucial factor because the GWPs differ widely in the different incineration scenarios.

When studying the effect of the costs from the perspective of existing waste treatment methods, the maximum difference in relative costs to Scenario 0 was only 1%. This means that the main differences were achieved in GWPs. Therefore, the treatment location could have been decided mainly based on the GWP results by using environmental criteria in the procurement. The environmental criteria make it possible to achieve greener procurements in the field of MSW management. Nowadays, waste management companies are more familiar with making greener waste collection procurements by taking into account transportation emissions when invited to make a tender. According to the results, the GWP of collection and transportation is quite a small part of the total emissions in the mixed MSW management. This result is inline with studies by Christensen et al. (2009) and Gentil et al. (2009). Both studies mention that GHG emissions from transport are relatively insignificant compared to other waste management systems. More notable GHG emission decrease can be achieved by focusing on the most significant factors and in this way focusing on the whole process rather than on one part of the process. The selected treatment location will have an influence for many years, until 2023 in the case area, hence making long-term and sustainable procurement decisions is critical. Environmental criteria as regards the waste treatment location procurements should be made in order to obtain clear instructions for procurement units.

Based on the forthcoming landfill ban and the GWP results, the main focus of the environmental criteria should be on the incineration plants, and such questions should be asked as: What is the annual electricity efficiency of the plant? What are the annual district heat and steam efficiencies? What are the substituted fuels in the area? Additionally, in the case of the fluidized bed combustor, it is crucial to know the share of SRF and the treatment of the rejects. The distance to the incineration plant is not a crucial factor from the point of view of the GWPs.

Further studies are needed to make clear the environmental criteria needed for waste treatment location procurements. The weight of different environmental criteria should also be considered so that the main focus is not only on the costs. Limitations in this study can be noticed in the cost calculations which are calculated completely from the point of view of the waste management company. In Scenario 1.3, the incineration plant is still under construction. Due to this, all the values in Scenario 1.3 are not known yet so more assumptions were required. In addition, the substituted electricity production in Scenarios 1.1–1.3 were calculated based on the electricity grid mix in Finland, consequently the benefits are highly country specific and the possible changes in electricity production in the future were not taken into account. It is noteworthy that this study was done from the point of view of GHG emissions. This should be taken into account when analysing the results. Further studies are needed to extend the analysis to other environmental aspects.

The results show that more factors linked to the waste incineration plants, rather than just the costs, should be taken into account in MSW management when inviting companies to tender for the combustion of mixed MSW. The results of the study can also be utilized more widely in the planning of waste management. It is already possible, when planning an appropriate site for a waste incineration plant, to identify the effect of the plant location on the utilization of the produced energy and on the substituted fuels.

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