Waste Management 58 (2016) 191–201

Contents lists available at ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Life-cycle assessment of a Waste-to-Energy plant in central Norway: Current situation and effects of changes in waste fraction composition

Carine Lausselet[a,*], Francesco Cherubini[a], Gonzalo del Alamo Serrano[b], Michael Becidan[b], Anders Hammer Strømman[a]

[a] *Industrial Ecology Program, Norwegian University of Science and Technology, NTNU, Trondheim, Norway*
[b] *SINTEF Energy Research, Trondheim, Norway*

ARTICLE INFO

Article history:
Received 17 March 2016
Revised 25 August 2016
Accepted 14 September 2016
Available online 24 September 2016

Keywords:
WtE
LCA
Challenging new waste fraction
Car fluff
Clinical waste
Wood waste

ABSTRACT

Waste-to-Energy (WtE) plants constitute one of the most common waste management options to deal with municipal solid waste. WtE plants have the dual objective to reduce the amount of waste sent to landfills and simultaneously to produce useful energy (heat and/or power). Energy from WtE is gaining steadily increasing importance in the energy mix of several countries. Norway is no exception, as energy recovered from waste currently represents the main energy source of the Norwegian district heating system. Life-cycle assessments (LCA) of WtE systems in a Norwegian context are quasi-nonexistent, and this study assesses the environmental performance of a WtE plant located in central Norway by combining detailed LCA methodology with primary data from plant operations. Mass transfer coefficients and leaching coefficients are used to trace emissions over the various life-cycle stages from waste logistics to final disposal of the ashes. We consider different fractions of input waste (current waste mix, insertion of 10% car fluff, 5% clinical waste and 10% and 50% wood waste), and find a total contribution to Climate Change Impact Potential ranging from 265 to 637 g CO_2 eq/kg of waste and 25 to 61 g CO_2 eq/MJ of heat. The key drivers of the environmental performances of the WtE system being assessed are the carbon biogenic fraction and the lower heating value of the incoming waste, the direct emissions at the WtE plant, the leaching of the heavy metals at the landfill sites and to a lesser extent the use of consumables. We benchmark the environmental performances of our WtE systems against those of fossil energy systems, and we find better performance for the majority of environmental impact categories, including Climate Change Impact Potential, although some trade-offs exist (e.g. higher impacts on Human Toxicity Potential than natural gas, but lower than coal). Also, the insertion of challenging new waste fractions is demonstrated to be an option both to cope with the excess capacity of the Norwegian WtE sector and to reach Norway's ambitious political goals for environmentally friendly energy systems.

1. Introduction

Waste-to-Energy (WtE) technologies consist of any waste treatment process that uses a waste source to create energy in the form of electricity, heat and/or transport fuels. The most common WtE technology used worldwide is the incineration of municipal solid waste (MSW) in a moving grate combustion system with combined heat and power production (CHP) (World Energy Council, 2013; Lombardi et al., 2015). Modern WtE has dual functions (Brunner and Rechberger, 2015) as: (1) Waste treatment – acts as a sink for pollutants with its thermal treatment processes destroying organic pollutants and extracting (and concentrating) chemical pollutants via advanced flue gas cleaning systems and transferring them into landfills and (2) Energy producer – recovery of useful energy from waste streams and possible reduction in the dependency on fossil sources. Owing to European legislation that discourages disposal to landfills as the environmentally and economically worst option (European Union Council, 1999), the number of WtE plants is steadily increasing in Europe, reaching 455 plants in 2012 (IEA Bionergy, 2013).

The Norwegian WtE sector is following this trend, and it has been a growing industry for the last decade, increasing from a total capacity of 1.3 million tonnes/year in 2010 to 1.7 million tonnes today. The sector currently accounts for 17 plants, spread all across Norway. The average throughput is 90% of the capacity, and the production is around 4 TW h for district heating networks, in addition to some electricity and process steam for industries located

---

* Corresponding author.
E-mail address: carine.lausselet@ntnu.no (C. Lausselet).

http://dx.doi.org/10.1016/j.wasman.2016.09.014
0956-053X/© 2016 Elsevier Ltd. All rights reserved.

near the plants (Becidan et al., 2015). Energy recovered from waste is the main energy source for district heating with a share of almost 50% (Statistics Norway, 2014), and 50% of the energy from the WtE sector is accounted for as renewable in Norwegian national statistics.

Several Norwegian WtE plants are currently suffering from low profitability. The main reason is that the processing capacity exceeds the waste produced in the Scandinavian market, where the gate fee is basically set by the Swedish plants (Becidan et al., 2015). A market with excess capacity will put the gate fees under pressure, which is not financially viable in the long run. Two alternatives are either to reduce the processing capacity or to increase the demand for processing capacity. An increase in demand for processing capacity can be achieved by importing waste from markets with insufficient capacity, i.e. countries where the waste would otherwise be landfilled and/or by the insertion—and thus co-combustion—of available challenging new waste fractions such as, in a Norwegian context, car fluff, clinical waste and wood waste.

The consideration of environmental aspects is playing an increasingly important role in the development of WtE projects (World Energy Council, 2013), and life-cycle assessment (LCA) is a methodology that has been used extensively within the last decade to evaluate the environmental performance of waste treatment systems (Arena et al., 2003; Björklund and Finnveden, 2005; Finnveden et al., 2005; Moberg et al., 2005; Buttol et al., 2007; Cherubini et al., 2008, 2009; Christensen et al., 2009; Rigamonti et al., 2009; Zhao et al., 2009a; Lazarevic et al., 2010; Consonni et al., 2011; Giugliano et al., 2011; Manfredi et al., 2011; Merrild et al., 2012) and in particular WtE technology such as incineration (Hellweg et al., 2001; Riber et al., 2008; Scipioni et al., 2009; Fruergaard et al., 2010; Fruergaard and Astrup, 2011; Boesch et al., 2014; Passarini et al., 2014; Burnley et al., 2015). LCA results give an overview of how various types of environmental impacts accumulate over the different life-cycle phases, providing a basis for identifying environmental bottlenecks of specific technologies and for comparing a set of alternative scenarios with respect to environmental impacts (Finnveden, 1999; Hellweg and Canals, 2014).

For WtE systems, the environmental bottlenecks are typically influenced by the energy recovery rate (Gentil et al., 2010; Giugliano et al., 2011; Tunesi, 2011; Turconi et al., 2011), the composition of the incoming waste (Astrup et al., 2011; Clavreul et al., 2014; Edjabou et al., 2015), the final disposal and leaching of the bottom ash (Doka and Hischier, 2005; Astrup et al., 2006; Hauschild et al., 2008; Allegrini et al., 2015a), the reuse of the bottom ash (Birgisdóttir et al., 2006, 2007; Allegrini et al., 2014, 2015b; Passarini et al., 2014), and the recycling of the metals (Morf et al., 2013; Boesch et al., 2014). Different technology options influence the performance of WtE plants (Tabasová et al., 2012; Arena and Di Gregorio, 2013; Ning et al., 2013; Passarini et al., 2014), and technology improvements can lead to drastic changes in their environmental profile; these changes are mostly due to the improved flue-gas cleaning achieved by stricter emission limits for species like Hg, As, heavy metals, and dioxins (Damgaard et al., 2010).

In general, WtE plants are found to be a robust technology for energy recovery from mixed waste (Astrup et al., 2009, 2011; Turconi et al., 2011; Brunner and Rechberger, 2015), and efficient WtE plants have been shown to be a competitive alternative to today's fossil fuel based energy system and complementary to a future energy system based on 100% renewable energy (Fruergaard and Astrup, 2011).

The combustion or co-combustion with energy recovery of challenging new waste fractions such as car fluff (Ciacci et al., 2010; Vermeulen et al., 2011; Passarini et al., 2012; Cossu and Lai, 2015) and clinical waste (Zhao et al., 2009b) are demonstrated to be more advantageous than landfills. Car fluff has awakened much interest in the EU in recent years, as 2–2.5 million tonnes are produced every year (Al-Salem et al., 2009), and the growing awareness of sustainability issues amongst the stakeholders is driving many industries to undertake environmentally conscious policies all along the value-chain (Subramoniam et al., 2009). Health care waste represents only a minor volume (e.g. 200–300 tonnes per year for St. Olavs Hospital, the main hospital in Central Norway), but its responsible and efficient treatment is a matter of public health (Harhay et al., 2009; Soares et al., 2013) and more research is needed given the trend in increased clinical waste production (Windfeld and Brooks, 2015). Most Norwegian healthcare facilities have closed down their own incinerators and have also experienced difficulty in finding facilities or actors to accept their waste, hence the importance of considering co-combustion with MSW in WtE plants.

The total amount of wood-based residues has been evaluated to 1 300 000 tonnes per year in Norway (Statistics Norway, 2011). However, this number includes many different fractions, and Statistics Norway does not have more details. A significant portion of wood waste is currently exported to Sweden, but local energy recovery would be preferred, in order to help Norway reach its ambitious political goals for environmentally friendly energy systems; Norway has implemented, through the EEA/EFTA agreement, the EU Renewable Directive with a national goal of 67.5% renewable energy sources by 2020 from a 2012 value of about 64.5%. For bioenergy, the aim is to double the production (including WtE) by 2020; from 14 to 28 TW h per year (Ministry of Petroleum and Energy, 2008).

Despite an increasing interest in LCA outcomes as a decision-support tool, LCAs of WtE in a Norwegian context are quasi-nonexistent (Bergsdal et al., 2005). Geographic and waste composition specificities have an impact on the results (Gentil et al., 2010; Turconi et al., 2011; Astrup et al., 2015), and the aim of this paper is to assess a Norwegian case by means of combining detailed LCA with operational data of a WtE plant located in Central Norway. Building on the state of the field, and following the recommendations provided by the recent reviews by Astrup et al. (2015), Laurent et al. (2014a,b), the specific objectives are: (1) to assess the current waste mix, (2) to assess the co-combustion of the current waste mix with car fluff, clinical waste and wood waste, (3) to provide a high resolution and geographical specificities on chemical waste composition, (4) to break down the results for any single chemical element constituting the waste, and influencing the results.

2. Methodology

2.1. System description

The WtE plant is divided into four subsystem areas (SAs), and the system description is presented in Fig. 1.

SA1 stands for the transport system. Household wastes are first collected throughout the city and then transported to the WtE facility while commercial and industrial (C&I) wastes are directly transported from their source to the WtE facility. The bottom ash is transported and handled to the municipal landfill. The fly ash (boiler ash and electronic precipitator ash) and filter cake are transported and handled to the hazardous landfill (located in Southern Norway).

For SA2, the conversion of waste to energy is largely based on the so-called lines 1 and 2 at the Heimdal WtE plant near Trondheim, which is owned and operated by Statkraft Varme AS, part of Statkraft, Europe's largest generator of renewable energy. The Heimdal plant supplies hot water to the district heating system