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Economic and environmental benefits of waste-to-energy technologies for debris recovery in disaster-hit Northeast Japan

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ABSTRACT

Since the 3/11 disaster, Japan has doubled its fossil fuel imports to supplement the nuclear power outage. The consequences of this growing dependence on energy imports threaten economic stability and environmental sustainability. More than 28 million tons of rubble and debris have also been washed up on the coastline of the disaster-hit Northeast Japan, presenting significant logistical and environmental challenges. The Government of Japan announced the construction of biomass power plants to simultaneously increase the renewable energy mix and to dispose of the debris. This study evaluates the economic and environmental benefits (capital and lifetime operation costs, non-renewable energy consumption, greenhouse gases (GHG), particulate matter equivalent and sulphur dioxide equivalent emissions) of advanced waste-to-energy biomass technologies, comparing (i) traditional biomass direct combustion with combined heat and power system, (ii) gasification combined with diesel cycle engine, (iii) Fischer-Tropsch combined with diesel cycle engine, and (iv) biomass fermentation for ethanol fuel production. Results show that the gasification pathway is the most energy efficient and the least expensive modern alternative for energy production, but has worse environmental performance compared to higher-cost biorefineries. On the other hand, the co-production of liquid fuels and electricity results in lower local environmental impacts, but the unit cost of energy produced is more than double that of traditional technologies. Fischer-Tropsch is lower cost and cleaner than ethanol plants, making it the more desirable option of the biorefinery technologies.

1. Introduction

On March 11, 2011 (hereafter 3/11), the most powerful earthquake in Japan's recorded history hit the Northeast coast of the country. The quake of magnitude Mw 9.0 triggered a devastating tsunami over the coastline, from Aomori up to Chiba prefecture. The waves wiped out a strip of the coastline, resulting in more than 20,000 causalities and causing extensive damages to more than 300,000 buildings and major infrastructure (Chagué-Goff et al., 2012). The direct economic damages were estimated at 16.9 trillion JPY (US$141 billion), turning it into the costliest natural disaster in the world history (GoJ, 2014).

Besides the human and material losses, the environmental impacts of the disaster were substantial. Following the tsunami, large areas of farmland were flooded with salty water and contaminated by sea sediments, which led to long-term soil contamination of high fertile agricultural land by metal and metalloid compounds (see detailed reviews in Mimura et al., 2011; Szczuciński et al., 2012). Along the coast, chemical processing plants, fuel refineries and various manufacturing industries also suffered major damages as the tsunami toppled materials and triggered several fires and hazardous substance spills. While the seriousness of the contamination is difficult to assess (Bird and Grossland, 2011), shortly after the disaster the Japan Society of Material Cycles and Waste Management disclosed data including types and locations of carcinogen compound spills (Misuzu Asari, et al., 2013). Furthermore, the Ministry of Environment has conducted monitoring activities for soil and groundwater in the affected area, concluding that high levels of hazardous chemicals were found near the facilities where the particular detected chemicals were stores (Inui et al., 2012).

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The 3/11 disaster also trigged an unprecedented solid waste crisis. The tsunami washed up more than 28 million tons of rubbles and debris on the coastline of disaster-hit Northeast Japan. The management of the debris has become a major financial and technological challenge, far outstripping the waste management capacity in the three most affected prefectures (Fukushima, Miyagi, and Iwate) (Asari et al., 2013; Ranghieri and Mikio 2014). For instance, in Ishinomaki city (Miyagi Prefecture), the equivalent of 103 years of solid waste generated in the city under normal conditions has been collected, totalling 6.5 million tons of debris (UNEP, 2012).

The removal and treatment activities conducted by the Ministry of Environment have progressed quickly. The disposal of debris and tsunami deposits was nearly completed by March 2014, except for Fukushima prefecture, where activities are still continuing (as at March 2015). About 16.5 million tons of debris and 10 million tons of tsunami deposits have been removed and treated (GoJ, 2014; MOE, 2014).

In the aftermath of the accident, nearly 30% of the country's nuclear power supply was put out of service and its future restart is uncertain given the strict guidelines for disaster countermeasures defined by the newly created Nuclear Regulation Authority (*Genshiryoku Kisei Iinkai*, NRA) (Portugal-Pereira and Esteban, 2014). Meanwhile, the country has doubled its Liquid Natural Gas and Heavy Fuel Oil imports to make up for the nuclear power outage. In less than nine months, the carbon footprint of electricity generation rose by 33%, from 384 to 509 g of carbon dioxide equivalent (CO_{2e}) per generated kWh (Portugal Pereira et al., 2014), while the trade deficit hit a record high of 2.56 trillion JPY ($US 31 billion) in 2011, putting further strains on an already fragile economy (MOF, 2012).

Over the last decade, Japan has launched remarkable actions to boost renewable energy generation, in particular from biomass. The central Government announced the 'Biomass Nippon Strategy' in 2002 to promote the production, collection, and conversion technologies of biomass as an energy resource (Kuzuhara, 2005; Matsumura and Yokoyama, 2005). Programs such as 'Biomass town' and 'Promotion of biofuels' have been implemented with the objective of stimulating rural economies and primary sectors. The Government also introduced a Feed-in Tariff (FIT) scheme in July 2012 to increase the share of renewables in electricity generation to guarantee providers a premium price which covers the extra cost of producing electricity from renewable resources. Under this system, wood and waste-based electricity will be paid at 13.65–33.60 JPY kWh^{-1} (0.163–0.402 US$ kWh^{-1}) (METI, 2012).

Aspiring to kill two birds with one stone and leveraging the financial incentives to boost renewable energies in Japan, the Government has announced the implementation of four biomass Combined Heat and Power (CHP) plants to recover wood and other combustible disaster debris. Three plants with the nominal capacity of 5 MW will be implemented in Miyako (Iwate), Kesennuma and Ishinomaki cities (Miyagi) and a smaller facility of 1 MW will be installed in Tagajo city (Miyagi). The plants, located near lumber and paper mills, are expected to burn a total of 200 kt of waste per year, with a total capacity of 16 MW of electricity. Once the debris from the disasters is used up, the plants will be supplied by wood waste from the mills for power generation (Kyodo, 2012). Although this is an effective strategy to enhance the renewable energy share of the electricity generation mix and to tackle disaster debris, direct combustion technologies present low energy efficiency and result in high amount of contaminated ashes. Thus, other advanced waste-to-energy (WTE) technologies need to be assessed in order to identify the most cost-effective and environmentally friendly alternatives. Advanced WTE technologies are particularly important as a cost-effective method to dispose non-recyclable waste and simultaneously mitigate climate change. Carbon dioxide emissions derived from a biogenic source are considered to be carbon neutral and therefore do not contribute to the national inventory. In this way, WTE processes yield extensive climate mitigation benefits, as methane emissions generated in landfills are offset and the demand of conventional fuels are reduced (Bosmans et al., 2013).

Several studies (Matsumura et al., 2005a, 2005b; Kamimura et al., 2012; Tabata and Okuda, 2012) addressed the sustainability and feasibility of electricity generation from biomass waste in Japan. However its scope is limited to conventional technologies in a city or national level, and it does not reflect the context post-3/11. Other studies have focused on comparing environmental impacts and feasibility of waste-to-energy technologies (Evans et al., 2010; Faaij et al., 1998). Furthermore, past research focus on the status of various cutting edge technologies, for instant for gasification (Faaij et al., 1997), FT-diesel (Reichling and Kulacki, 2011; Sunde et al., 2011), and cellulosic ethanol (Tijmensen et al., 2002; Hamelinck et al., 2005; Luo et al., 2009). This paper contributes to the literature by evaluating the environmental sustainability and cost-effectiveness of advanced waste-to-energy technologies in a post-3/11 context in Japan. The study applies a life cycle assessment approach to quantify 'cradle-to-gate' global and local environmental impacts and generation costs of different waste-to-energy technologies.

This study seeks to assess the economic and environmental benefits of WTE technologies as a waste management strategy to handle the disaster-generated debris post-3/11. It compares the capital and lifetime operation costs, non-renewable energy (NRE) consumption, global warming potential (GWP), particulate matter formation (PMF), and terrestrial acidification potential (TAP) of four biomass combustion technologies. These technologies are (i) direct biomass combustion with combined heat and power (CHP) system, (ii) gasification combined with diesel cycle engine, (iii) Fischer-Tropsch (FT) combined with diesel cycle engine, and (iv) biomass fermentation for ethanol fuel production with CHP system. To assess the environmental impacts of each alternative, a life cycle assessment has been conducted, following ISO 14040 and 14044 standards (ISO, 2006a, 2006b). The cost assessment is based on the system boundaries assumed in the life cycle analysis.

2. Background

This section discusses the state-of –the art storage and disposal activities (as at March 2015) in the disaster-hit prefectures in Tohoku region, and briefly describes the composition of the tsunami debris and rubble generated. The technical characterisation of evaluated WTE technologies and its potential to mitigate the impacts of tsunami debris and rubble are also examined.

2.1. Tsunami debris biomass characterization

The discussion in this paper is limited to debris and rubbles accumulated on the coastline of Iwate, Miyage and Fukushima prefectures after the 3/11 disaster. Table 1 presents the volume of generated and disposed waste in the disaster-hit prefectures (as at March 2015). While Miyage and Iwate prefectures were most severely affected by debris and rubbles, these regions were the fastest in disposing the waste. On the other hand, in Fukushima prefecture, removal works are moving slowly given the high level of contaminated waste and radiation risk. Overall more than 2 kt of debris, equivalent to 6% of total generated waste, is yet to be treated and disposed (MOE, 2014).

The tsunami brought up a great variety of materials, including sand, mud and other bottom materials, which have been sorted into heterogeneous piles of debris and rubble. The floating debris is mainly composed of materials from collapsed houses and