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Scenario analysis for sustainable woody biomass energy businesses: The case study of a Japanese rural community

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ABSTRACT

Woody biomass is widely used as a renewable energy source to produce electricity and heat, with the goal of reducing CO_2 emissions, enhancing energy security, and rejuvenating rural economies. In Japan, the energy usage of woody biomass is currently incentivized by feed-in tariff (FIT) programs. However, a variety of unpredictable factors (*e.g.*, a drastic change in national energy policy and feedstock supply) might undermine the sustainability of woody biomass energy businesses. In order to clarify conditions for designing sustainable woody biomass energy businesses from environmental and economic viewpoints, this paper proposes a method for undertaking scenario analyses where the influences of future uncertainties are analyzed. For quantitative assessment, a woody biomass energy business is modeled as a sequence of processes using a discrete event simulation technique. A case study is carried out with a particular focus on the energy business with a 10 MW woody biomass power generation plant in a Japanese rural community in the period of 2015–2034 (20 years). The results reveal that the business has potential to gain economic profit and halve CO_2 emissions when compared with the worst case scenario. Critical factors for enhancing the sustainability of the business include collecting the amount of wood residue used for electricity generation and keeping the selling price of electricity from woody biomass at over 35% of the current price.

1. Introduction

The utilization of woody biomass energy has been growing worldwide in order to reduce CO_2 emissions, enhance energy security, and rejuvenate rural economies (Bracmort, 2016; International Energy Agency (IEA), 2015). The share of bioenergy (*e.g.*, solid biomass, biofuels, and biogas) in the world's primary energy demand is projected to increase to 1830–2331 Mtoe (corresponding to 9–15% of the entire demand) by 2040, from 1376 Mtoe (corresponding to 10% of the entire demand) in 2013 (IEA, 2015). Biomass energy is characterized by being storable, while many of other renewable sources (*e.g.*, solar, wind, and marine energy) are of intermittent nature (Fiorese et al., 2014).

There are various energy conversion technologies for woody biomass, such as combustion, gasification, and pyrolysis (Fiorese et al., 2014; Zhang et al., 2010). However, one of critical obstacles for the penetration of woody biomass energy is higher initial costs relative to fossil fuel-based electricity production systems (Bracmort, 2016). Therefore, a feed-in tariff (FIT) program plays an important role in promoting the deployment of woody biomass energy businesses (Conture et al., 2010; Ministry of Economy, Trade and Industry, Japan (METI), 2015a; Moore, 2013). In this paper, a woody biomass energy business is defined as an economic activity that produces and sells energy in any form (*e.g.*, electricity and heat) using woody biomass (*e.g.*, round wood, branch, bark, and sawn wood) as an energy source.

Given the lifespan of energy production infrastructure for woody biomass (*e.g.*, biomass power generation plant), the sustainability of woody biomass energy businesses must be ensured in a long run (*e.g.*, 20–30 years). However, it is not easy to design sustainable businesses due to a variety of future uncertainties associated with the businesses. Examples of uncertain factors include feedstock supply, wood price, FIT scheme, and grid electricity price (Röder et al., 2015). Commonly, these factors have the nature of unpredictable changes over time or even in a shorter period of time. For example, in Germany, the price of wood chips was approximately 45–50 EUR/t in 2003, but was almost doubled

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to approximately 80–90 EUR/t in 2010 (German Biomass Research Centre, 2011).

With the aim of clarifying conditions for sustainable businesses taking into account such future uncertainties, this paper proposes a method for undertaking scenario analyses of woody biomass energy businesses. A scenario analysis is useful for assuming a possible range of futures, based upon which effective strategies and actions are to be sought (Foresight Horizon Scanning Centre, 2009; Kishita et al., 2016a, 2016b). Thus, the proposed method would help to analyze the influence of various uncertain factors on the business. For quantitative assessment of scenarios from both environmental and economic viewpoints, we represent a woody biomass energy business as a sequence of processes (*e.g.*, material extraction and energy conversion processes) using a discrete event simulation technique (Kishita et al., 2009; Umeda et al., 2000). One characteristic of the method is that, in the energy conversion process, we employ Dulong's formula in order to estimate the heating value of wood by assuming particular moisture content of wood. Dulong's formula was originally developed to estimate the higher heating value of coal based on the weight fractions of four elements (i.e., carbon, hydrogen, oxygen, and sulfur) (Selvig and Gibson, 1945). The case study of a Japanese rural community is described to gain insight into conditions for sustainable woody biomass businesses.

The remaining part of the paper is structured as follows. Section 2 mentions a review of related work and problems in designing sustainable woody biomass energy businesses. Section 3 proposes a method for scenario analyses of woody biomass energy businesses. Section 4 describes the case study of a Japanese rural community in order to examine the effectiveness of the proposed method in Section 3. Section 5 discusses conditions and challenges for achieving sustainable businesses. Finally, Section 6 concludes the paper.

2. Design of sustainable woody biomass energy businesses

2.1. Deployment of woody biomass energy

In many countries across the world, such as European countries, China, and Japan, FIT programs have accelerated the deployment of woody biomass energy (IEA, 2014). In Germany, Renewable Energy Act with feed-in tariffs, which was legislated in 2000, has increased the share of renewable-based electricity generation to 27.8% (160.6 billion kWh) in 2014, of which biomass accounted for 30.6% (49.1 billion kWh) (Federal Ministry for Economic Affairs and Energy, Germany, 2015).

In Japan, the national government enforced a FIT scheme in 2012, resulting in an increasing number of woody biomass power generation plants in operation (see Fig. 1). As of 2015, approximately 70% of all (35 out of 51) plants had electricity generation capacity of 5 MW or more. This is because larger-scale plants have higher energy conversion efficiency. One characteristic of Japan's FIT scheme is that the purchase price for the electricity from unused wood (*e.g.*, thinned wood) is higher than that from other wood (*e.g.*, sawn wood from timber mills and waste wood from demolished buildings). Since the Japanese forestry industry is less cost-competitive compared with other countries such as Canada, imported wood meets over 70% of the total wood demand in Japan (Ministry of Agriculture, Forestry and Fisheries, Japan (MAFF), 2015). Therefore, the Japanese government introduced the FIT scheme to economically incentivize the usage of forestry stocks within the country (METI, 2015a).

2.2. Related work

Research on the supply chain analysis of woody biomass has been progressed (*e.g.*, Mantau, 2015; Whalley et al., 2017). For example, Kalt (2015) provided the national biomass streams in Austria, taking into account import, export, and various types of uses (*e.g.*, food and energy). Focused on the energy use of woody biomass, Berndes et al. (2003) analyzed the possible contribution of the biomass in the future global energy supply to 2100. Likewise, Lauri et al. (2014) provided an economic analysis of woody biomass energy potential on global scale to 2050, by which they showed that woody biomass could satisfy 18% of the world's primary energy consumption in 2050. From the viewpoint of policy instruments, Thornley and Cooper (2008) analyzed the relationship between bioenergy growth and national energy policies (*e.g.*, subsidies and environmental tax).

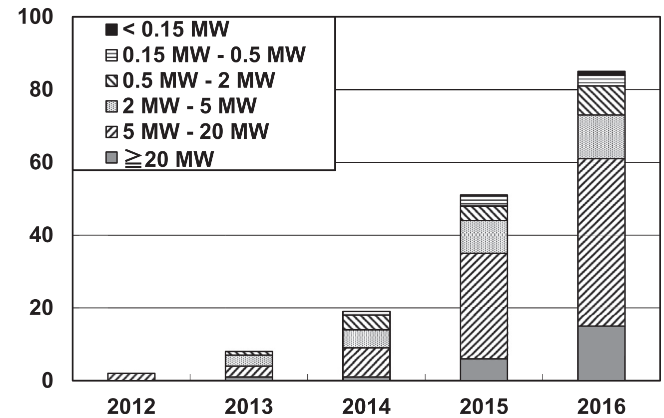

Fig. 1. Number of woody biomass power generation plants in Japan (Japan Wood Energy Co., Ltd., 2015; estimated data for 2016). The classification is based on the capacity of power generation in MW.

A broad range of research on sustainability assessment of such businesses has been published in several journals, including Journal of Cleaner Production and Applied Energy. Focusing on an environmental aspect, a diversity of life cycle assessment (LCA) studies have been conducted in a number of papers (Seifert, 2014; Wiloso et al., 2014; Wolf et al., 2015). Klein et al. (2016) applied an LCA to analyze the environmental impacts (*i.e.*, greenhouse gas emissions, primary energy consumption, and particulate matter emissions) of woody biomass supply chains, including harvesting and transportation. Murphy et al. (2014, 2015, 2016) analyzed the environmental impacts of biomass supply chains in Ireland, where, in particular, Murphy et al. (2016) carried out the life cycle assessment of biomass co-firing in the existing peat-fired power stations and biomass combined heat and power (CHP) plants. Thakur et al. (2014) applied an LCA in the use of forest harvest residues for power generation, covering power plant sizes of 10–300 MW. Monteleone et al. (2015) carried out an LCA of pellet boilers and compared their environmental impacts to those associated with fossil fuel boilers.

Related to economic and business aspects, many scholars have analyzed woody biomass energy businesses using different models as follows. Fiorese et al. (2014) assessed the potential cost reduction of bioenergy technologies (*e.g.*, combustion, gasification, and pyrolysis) based on experts' judgments. Bazmi et al. (2015) proposed an optimization model for decentralized biopower generation systems to reduce the overall generation cost. Brown et al. (2009) analyzed the total cost and exergy efficiency of a wood gasification system with the particular focus on electricity generation cost and tar control. Mobini et al. (2014) analyzed the effect of integrating torrefaction into the supply chain of wood pellet production in economic cost and CO_2 emission, using a discrete event simulation approach. Moore et al. (2013) analyzed the economic

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