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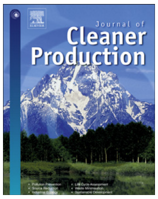

Life cycle assessment of small-scale combined heat and power plant: Environmental impacts of different forest biofuels and replacing district heat produced from natural gas

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A B S T R A C T

Forest biomass is used in many countries as an abundant and easily accessible source of renewable energy. While forest biomass has certain advantages in terms of carbon sink capability, it cannot be considered an emission-free energy source, and the environmental differences among various forest biomass sources have been unclear. This study uses life cycle assessment for two purposes. The first is to quantify the environmental impacts of the energy production of a small-scale, combined heat and power production plant utilizing different forest biomasses. The second aim is to estimate the change in environmental impacts on district heat production from natural gas when partially replacing it by heat from the combined heat and power plant. The environmental impacts include global warming potential, acidification potential, and eutrophication potential. The calculated environmental impacts of utilizing different forest biofuels in the CHP plant in relation to produced energy are 2.2–5.1 $g_{CO2,eq.}/MJ_{energy}$ excluding biogenic carbon emission, 59–66 $g_{CO2,eq.}/MJ_{energy}$ with biogenic carbon emission, and 133–175 $mg_{SO2,eq.}/MJ_{energy}$ and 18–22 $mg_{PO34-,eq.}/MJ_{energy}$ with pellets, showing the highest values. The results indicate that by using forest biomass instead of natural gas in energy production, the global climate impacts are reduced when biogenic carbon is excluded, while the local effects are higher (acidification potential and eutrophication potential). Including biogenic carbon reduces the calculated climate benefit since the total emissions end up being 4–7% over those of natural gas use. The potential benefits need to be weighed against the possible drawbacks.

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1. Introduction

Most of the current energy production methods cause adverse environmental impacts and often involve considerable resource uncertainties (Hammond, 2004). The (European Union, 2009) has targeted a 20% reduction in greenhouse gas (GHG) emissions by 2020 from the 1990 levels, and renewable energy production is deemed the key solution. So far, there has been widespread enthusiasm related to renewable energy generation; therefore, an environmental impact evaluation of a new bioenergy production process is obviously required.

Biomass is a renewable energy source with the highest potential to contribute to the energy needs of modern society worldwide (European Commission, 1997). Wood and other forms of biomass, including energy crops and industrial, agricultural (Cherubini and Ulgiati, 2010), and forestry waste, are some of the main renewable energy resources available (Bridgewater, 2004). In Finland, the use of renewable sources for district heating has increased rapidly in recent years, and biofuels have contributed an important share in the total energy production to date (Salomón et al., 2011). With its abundant forest resources, Finland has the potential to develop renewable energy generation from forest biomass by utilizing combined heat and power (CHP) plants. Wood chip (WC) fuel chains have been examined, and improvements in the logistic chain have been sought (Tahvanainen and Anttila, 2011). The WCs have been produced from small-diameter wood and wood residues. Additionally, industrial residues, such as cutter dust and sawdust, have been used to produce pellets for small-scale CHP plants.

To contribute to the mitigation of climate change, renewable energy technology has to produce less emission than the

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conventional fossil fuel-based energy production. Life cycle assessment (LCA) examines the potential environmental impacts throughout a product's life cycle, from raw material acquisition to final disposal (ISO 14040, 2006). LCA offers a powerful tool to analyze environmental impacts, including climate change effects of energy production methods. LCA has been conducted on photovoltaic systems (Sherwani and Usmani, 2010), biogas (Ishikawa et al., 2006), biomethane (Uusitalo et al., 2014), bioethanol production (Sandilands et al., 2009), and wind power production (Schleisner, 2000). Caserini et al. (2010) state that GHG savings can be obtained in comparison to conventional fuels if biomass supplying distance is less than 600 km. Furthermore, Pehnt (2008) found that most micro cogeneration systems are superior in GHG reduction potential compared to average electricity and heat supply as well as to state-of-art separate production. Kimming et al. (2011) concluded that utilizing agricultural biomass in small-scale CHP plants result to GHG emission reductions in comparison to fossil fuel-based systems. CHP can play an important role in the energy system. For example, CHP reduces fuel costs and contributes to the optimization of total energy costs, capacity, and societal costs (Østergaard, 2009).

Cherubini and Strømman (2011) state that in most LCA studies, replacing fossil energy with bioenergy results in a significant net reduction in GHG emissions. Eriksson et al. (2007) found that district heat and electricity production from biofuels would be environmentally sound strategy when comparing it to waste combustion and natural gas in Sweden. Similarly Kimming et al. (2011) concluded that small scale CHP production from agriculture biomass would be suitable in rural areas in Sweden and would reduce emissions considerably in comparison to fossil-fuel based system. According to a study by Caserini et al. (2010) net GHG emission savings are obtained when comparing biomass combustion to fossil fuel use when supplying distance is less than 600 km but the more locally affecting emission such particle matter, PAH and VOC are a negative environmental effect from the biomass combustion. The common practice of assuming the carbon neutrality of biomass use has also been challenged (Cherubini et al., 2016). While forest biomass has certain advantages in terms of carbon sink capability, it cannot be regarded as an emission-free energy source (Cherubini et al., 2016), and the environmental differences among various forest biomass sources are unclear.

LCA has been also used in calculating GHG emission impacts of biomass production chain (Jäppinen et al., 2014; Wihersaari, 2005) and use in energy production (Leino et al., 2016) in Finland. Jäppinen et al. (2014) concluded that harvesting residues and small diameter wood are most attractive sources for wood-based fuels. Leino et al. (2016) concluded that from climate change perspective, saw mills would benefit from using saw mill residues in CHP production. Wihersaari (2005) found that reductions GHG emission reductions could be as much as 98%. However, few studies have focused on other impact categories, such as acidification potential (AP) and eutrophication potential (EP) when biomass fuels replace fossil fuels. Distributed CHP production using wood-based fuels can help mitigate global GHG emissions by replacing fossil fuels. However, the impacts might be different when examining more locally affecting emissions that cause acidification and eutrophication. In addition, there is a research gap on the impact a small scale CHP plant utilizing wood-based fuels would have as a part of district heat production system. A small scale CHP plant could provide enough district heat during warmer months of the year when there is not enough heat load for large scale CHP plant and also provide renewable electricity.

Thus, this study's first goal is to quantify environmental impacts, including the global warming potential (GWP), the AP, and the EP of producing energy in a small-scale CHP plant that utilizes different forest biomasses. The second goal is to compare the environmental impacts of producing district heat solely from natural gas against producing part of the district heat in the CHP plant in the selected case area. The examined wood-based fuels include WCs from forest residues and small-diameter wood, as well as pellets from cutter dust and sawdust.

2. Methods

2.1. Case study

The technology examined in this study is a small-scale CHP plant using forest biomass, located in the Saimaanharju area in the municipality of Taipalsaari, Finland. The plant is used alongside the natural gas heating plant. The total heat demand in the Saimaanharju district heat grid averages 7000 MWh/a (Neuvonen, 2014). The small-scale CHP plant uses wood chips or pellets as fuels in a grate furnace. The combustion gases are directed to a heat exchanger where the heat is transferred to compressed air. The air is then used in a micro gas turbine to produce electricity. The aim of using pressurized air is to have reliable, error-free operations as much as possible. In addition to the electricity, the plant also produces heat which is directed to the district heating network and replaces the heat produced by natural gas (Karhunen and Koskelainen, 2013). A simplified process chart is presented in Fig. 1. According to an updated simulation of the Saimaanharju CHP plant, it uses 580 kW (4400 MWh/a) of fuel and produces 106 kW (approximately 790 MWh/a) of electricity and 400 kW (approximately 3000 MWh/a) of heat. The electric efficiency is 18%, with a heat efficiency of 68% (Koskelainen, 2012). More information about the Saimaanharju CHP plant modeling has been reported (Sipilä et al., 2015), and the CHP plant has been compared with other distributed energy systems (Väisänen et al., 2016). More information about the Saimaanharju CHP plant in general (Sipilä et al.), Matlab modeling (Karjalainen, 2015) and comparison of the CHP plant with other distributed energy systems (Väisänen et al., 2016).

First, this study calculates and compares the environmental impacts of using wood-based fuels for the small-scale CHP plant. Second, the environmental impacts of producing district heat solely from natural gas are compared against partially producing heat from the small-scale CHP plant in the Saimaanharju area. The system boundaries for calculating the emissions of energy production in the CHP plant and the changes in the environmental impacts of the Saimaanharju district's heat production are represented in Fig. 2.

2.2. Life cycle assessment

LCA was performed in accordance with ISO standards 14040 and 14044 (ISO 14040, 2006; ISO 14044, 2006). The functional unit was 1 MJ of produced energy (21% electricity and 79% heat); Fig. 2 shows the two system boundaries, as well as the reference flows. The

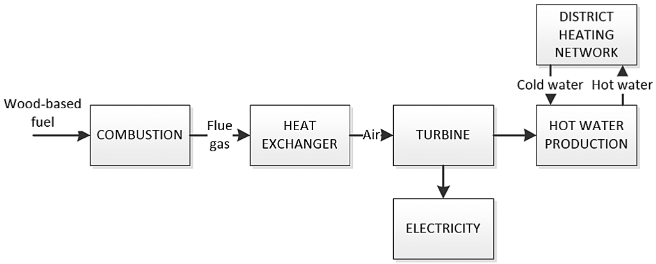

Fig. 1. Simplified flow chart about small-scale CHP plant investigated in the study.

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