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A regional model for sustainable biogas electricity production: A case study from a Finnish province

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HIGHLIGHTS

- ▶ Regional model is introduced for biogas electricity production.
- ▶ The aim is to increase electricity production and to decrease GHG emissions.
- ▶ The model is tested in a Finnish province, North-Savo.
- ▶ Locations of biogas plants and potential feedstock fractions are determined.
- ▶ Results are illustrated in North-Savo map.

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ABSTRACT

A regional model for sustainable biogas electricity production was formulated and tested for a Finnish province, North-Savo. By using the model the aim was to support decision making for reducing greenhouse gas (GHG) emissions and increasing renewable energy (RE) production in the studied region in the biogas electricity production system. The system boundary of the model included transportation of waste, biogas production, heat and electricity production, as well as the delivery of heat and digestate to the end users. When electricity production was maximized in the studied region, the electricity production and GHG emissions were 20 GW h/year and 24 kt/year of CO_2 equivalent, respectively. When GHG emissions were minimized, the electricity production and GHG emissions were 20 GW h/year and 23 kt/year of CO_2 equivalent, respectively. By producing electricity of 20 GW h/year, the maximum GHG reductions were roughly 74% of the theoretical maximum GHG emissions of 90 kt/year of CO_2 equivalent in both cases. The regional electricity production potential of 20 GW h/year was only 21% of the maximum electricity production potential of 94 GW h/year. The locations of biogas plants, regional relative GHG emissions, potential feedstocks and regional electricity production were optimized in both cases in the studied region.

1. Introduction

The EU administration has endorsed a policy to transform Europe into an energy-efficient and low-carbon society which could be fostered by taking biogas production into much larger use. Two of the binding targets by 2020 are to reduce GHG (green house gas) emissions by 20% below the level in 1990 and to increase the renewable energy production up to 20% of the total energy consumption [1]. European comission reinforces these 2020 targets by requiring its member states to support sustainable renewable energy production (Directive 2009/28/EC). It was lately reported that biogas production have sufficient GHG savings to fulfill the GHG saving requirements and also the sustainability criteria according to Directive 2009/28/EC [2]. Electricity production from biogas is also reported to be the only renewable energy production process that has the major GHG reduction potential compared to others such as hydro power, electricity production from wood and wind power [3].

In Finland regional restrictions limit the utilization of biogas energy potential of 25 TW h/year for electricity and heat production. Crops, manures, municipal solid waste and waste slurries had shares of 82%, 10%, 7.6% and 0.4%, respectively of the total biogas energy potential which equals to 6.6% of the total energy consumption [4]. However, the total biodegradable waste energy potential lies mostly in the rural areas. In biogas production systems feedstock fractions are reported to have maximum transportation distances which equal to zero net energy balance over the

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whole production chain [5,6]. In CHP production the electricity production is also limited by the regional heat demand including the heat delivery energy consumption and the heat losses. This leads to a question how much and where biogas electricity would be produced in the selected target area in sustainable way by taking into account these regional restrictions. Further question is that what kind of feedstock fractions would be the most desired.

The latest models seem not to answer to these questions, although many researches had been done with a focus on energy balance calculations, regional carbon dioxide calculations and regional life cycle analysis [7–9]. For example, MCDA (Multi-criteria decision analysis) was used in regional biogas production modeling in Ireland [10], which was carried out to find the regional potential of biogas production to replace fossil fuels. Multi-agent simulation model (MAS) was used in Germany to forecast the regional diffusion of electricity production technology from biogas [11] in order to provide sound strategies for the decision makers about the effects of German feed-in tariff on biogas technology diffusion.

In order to promote sustainable renewable energy production the regional model for sustainable biogas electricity production system was formulated. The system boundary of the model includes transportation of feedstock, heat and power production as well as the delivery of heat. The model is carried out by preparing the input data from the studied region from a Finnish province (Section 2), formulating the model (Section 3) as well as optimizing the electricity production and GHG emissions by using a metaheuristic algorithm (Section 4).

2. Target area and data preparation

The input data from North-Savo consists of defined regional heat consumption- and feedstock data. The regional heat consumption is defined as a sum of all defined heat consumers inside an area with a radius of 5 km. Suitable biodegradable waste feedstock fractions are divided into three categories, manures, spoilt grass silage and municipal waste.

At the end of 2010, the population in North-Savo was approximately 0.25 million, living in an area of 16.8 thousand km^2 [12]. If the electricity consumption per inhabitant in North-Savo is assumed to be same as the average of 17 MW h in Finland in 2007 [13],[14], the electricity consumption in North-Savo is calculated as 4.2 TW h.

2.1. Regional heat consumption data

Heat consumption is considered in residential apartments, industry, public buildings and cattle farms as well as pig farms. Some of the industry and public buildings are using district heat, whose heat consumption is known in each district heating plant [15]. The heat consumption in residential apartments is based on the assumption of specific heat consumption of 130 kW h/(m^2 year) [16] and an average flat area in 250 m grids [17]. Heat consumption is also considered in Finnish cattle and pig farms [18]. The annual heat consumption of cattle and pig units is assumed to be 1000 kW h and 250 kW h, respectively [19].

2.2. Feedstock data

The properties of the main feedstock fractions are based on literature values, data bases and estimations (Table 1). The origin of domestic animals and field areas in grass silage production on each farm were retrieved from Finnish farm data base [18]. The origin, mass and total solid concentration of municipal based waste was retrieved from Finnish waste database [20].

Methane production of manure fractions was calculated (Table 1). Methane yield (MPR) of pig slurry manure was 8.4 N m^3 per wet weight (ww) ton when the total solids (TS) was 3.5% of wet weight [21], volatile solids (VS) was 75% of total solids [22] and the methane yield per ton of VS was 320 N $m^3 CH_4$ [23]. Methane yield of cow slurry manure was in similar way 10 N m^3/(t ww) when the total solid concentration was 5.5% [21], volatile solids was 85% of total solids [22] and methane yield per ton of VS was 210 N $m^3 CH_4$ [24]. When horse-, sheep-, goat- and duck-solid manure volatile solids were assumed to be 75% of wet weight [22], TS concentrations are known [21] and methane yields per ton of VS were also assumed to be 210 N $m^3 CH_4$ methane yields in terms of N m^3/(t ww) (MPR) are shown in Table 1.

3. Regional model

The regional model was formed for biogas heat and electricity production system which was used for optimizing the electricity production and GHG emissions by a using a metaheuristic algorithm (Section 4). The system boundary of the model consists of transportation of waste, heat and electricity production in the biogas plant as well as the heat delivery to the end user (Fig. 1). The system boundary is defined so that only energy input E_{TRi} is needed in waste transportation. The energy outputs are electricity E_{ELi} and heat E_{PHi} delivered to the end user. Biodegradable waste, also called as feedstock, is transported into the biogas plant. Digestate is transported back to the origin of waste. The system boundary of the biogas plant includes heat and electricity production from biogas, reactor heating, sanitation, mixing, pumping as well as minor energy devices (Fig. 1). The net output of heat and electricity is

Table 1
The properties of manures, spoilt grass silage and municipal waste fractions.

Substance	MPR $\left(\frac{\text{N m}^3\text{CH}_4}{\text{t ww}}\right)$	ρ_{ij} (kg/m^3)	TS_{ij} (% ww)	Description
Manures				
Cow slurry manure	10[b]	992.7 [21]	5.5 [21]	16 t ww/cow[a]
Pig slurry manure	8.4[b]	997.1 [21]	3.5 [21]	2 t ww/pig[a]
Horse solid manure	49[b]	527.8 [21]	31.4 [21]	6 m^3/horse[a]
Sheep solid manure	54[b]	589.6 [21]	34 [21]	1.5 m^3/(sheep/goat) [25]
Duck solid manure	76[b]	621.5 [21]	48 [21]	0.05 m^3/duck [25]
Spoilt grass silage:				Grass silage yield of 17.64 t ww/ha [26]
Bad quality grass silage	62.18 [27]	750[a]	31.8 [26]	1.47% of the total yield [27]
Left over grass silage	80 [27]	750[a]	31.8 [26]	1.79% of the total yield [27]
Municipal waste				
Household biowaste	(150–300)[b]	850[a]	50–100 [20]	300 N $m^3 CH_4$/(tTS) [28]
Potato waste	(53–66)[b]	900[a]	20–25 [20]	263 N $m^3 CH_4$/(tTS) [29]
Fatty residue	344 [30]	950[a]	30 [20]	
Fatty wastewater	232 [30]	950[a]	50 [20]	
Sewage sludge	(6–78)[b]	900[a]	3–35 [20]	205 N $m^3 CH_4$/(tTS)[a]

[a] Estimated value.
[b] Calculated value.