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A techno-economic assessment for replacement of conventional fossil fuel based technologies in animal farms with biogas fueled CHP units

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ABSTRACT

In this paper, a case study applied to an animal farm in Iran, covering both technical and economic aspects of biogas production using manure from livestock to replace fossil fuel used for heat and electricity generation is presented. The mentioned farm has 3058 dairy cows. Biogas production followed by small-scale combined heat and power (CHP) units based on a new dual fuel internal combustion engine (ICE) have replaced conventional technology used today, namely electricity from the grid and diesel fuel for heating via boiler technology. Results from the techno-economic studies reveal that alternative technology using biogas as fuel are superior compared to the conventional one, both from economic and environmental point of view. By evaluating the proposed model, the annual cost saving, percentage of system profitability index, and payback period are calculated as 73,159.31 $, 60.99% and 28.5 month, respectively. Replacing the conventional technology by biogas based technology results in 529.65 tons per year annual CO_2 emission reduction for this typical animal farm. Finally, a sensitivity analysis is elaborated in order to show how the profitability of biogas CHP plants would vary due to changes of some key parameters such as prices of diesel fuel, electricity and electricity buyback.

1. Introduction

World reduction of energy resources, increasing the greenhouse gas emissions and global warming along with the increase of energy demand and rising the price of energy have motivated researchers to find new shapes of energy which are renewable and clean [1]. Furthermore, increasing animal waste is considered as an important issue leading to significant environmental problems, if is not properly processed [2]. Biogas from manure is a renewable energy resource which can be used in many applications [3]. Biogas that is produced by anaerobic digestion (AD) of organic feedstock can burn in an internal combustion engine in a CHP plant to generate heat and electricity [4].

Anaerobic biogas is the outcome of decomposition of organic material by micro-organisms.

Biogas consist of 45–60% methane (CH_4), 25–45% carbon dioxide (CO_2), 2–7% water (H_2O) at 20–40 °C, 2–5% nitrogen (N_2), 0–2% oxygen (O_2), and less than 1% hydrogen (H_2), 0–1% ammonia (NH_3), and 0–6000 ppm hydrogen sulphide (H_2S) [4].

This research work presents a new feasibility study, including extensive sensitivity analysis with respect to key parameters, for using biogas in a CHP plant. A new regional techno economic mode is developed to evaluate the feasibility of using sustainable biogas CHP system in an animal farms. Using animal manure with an anaerobic digestion technology, biogas is produced, which is burned in a biogas CHP system with the electric power of 375 kW to supply the demand of heat and electricity. The modeling work is divided into 6 parts: determined the manure production of the dairy cow farm, modeling of the energy profile of the cow farm (including electrical and thermal demands), modeling of the biogas CHP plant, economic and environmental assessments and finally sensitivity analysis. The proposed model contains many valuable details, which can be used for planning and expansion of any cow farm and similar plants.

The extensive results obtained from the model illustrate that using biogas as fuel for generating electricity and heat can considerably reduce the consumption of primary energy and operating cost.

At the end of this study, a sensitivity analysis is accomplished to show how the profitability of the biogas CHP plant would vary due to changes of some key parameters such as diesel fuel, electricity and electricity buyback prices.

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Nomenclature

H_r^{BGCHP}	Rated thermal capacity of the biogas CHP system (kW)
Q_M	Maximum heat demand of the farm in a sample year (kW)
C_r^{BGCHP}	Electrical rated capacity of biogas CHP system (kW)
η_{th}^{BGCHP}	Thermal efficiency of biogas CHP system (%)
η_e^{BGCHP}	Electrical efficiency of biogas CHP system (%)
BG	Biogas required for supplying the farm's thermal loads (Nm^3)
HA	Thermal demand of the farm and digester per month on average (kWh)
E_{in}	Input energy required for supplying thermal loads (kWh)
HV_{BG}	Biogas heating value (kWh/Nm^3)
E_{BG}	Total monthly energy generated by the biogas fuel (kWh/month)
BG_{AD}	Biogas produced from livestock wastes (Nm^3/month)
E_o	Total energy that should be supplied by diesel fuel (kWh)
HV_{GS}	Heating value of diesel fuel (kWh/Liter)
Fuel	Required diesel fuel (Liter/month)
H	Operation hours (hour/month)
E_{total}^{BGCHP}	Total electricity generated by CHP system during a month (kWh)
E_{sell}	Excess electricity which is sold to the grid (kWh)
Ebuy	Electricity that should be bought (kWh)
EA	Electricity consumption of the farm and digester system (kWh)
CSR	Cost Saving Ratio (%)
C_{CONV}	Annual energy cost of the conventional system ($)
CBGCHP	Annual energy cost of the biogas CHP system ($)
CE_{Conv}	Carbon dioxide emissions of conventional energy system
CE_{BCHP}	Carbon dioxide emissions of Biogas CHP system
CERR	Carbon dioxide Equivalent Reduction Ratio index
FR_{CH4}	Fraction of methane in the biogas (Nm^3 CH_4/Nm^3 biogas)
GWP_{CH4}	Global Warming Potential of CH_4 (t CO_2e/t CH_4)
C_{CONV}^{IV}	Investment cost of conventional system ($)
C_{CONV}^{MT}	Annual maintenance cost of conventional system ($)
C_{CONV}^{EL}	Annual cost of purchasing electricity for the conventional system ($)
C_{CONV}^{GO}	Annual cost of purchasing diesel fuel for the conventional system ($)
C_{BGCHP}^{IV}	Investment cost of biogas CHP plant ($/kW)
C_{BGCHP}^{MT}	Biogas CHP's annual maintenance cost ($)
C_{BGCHP}^{EL}	Cost of purchasing electricity from the grid for the biogas CHP system ($)
C_{BGCHP}^{GO}	Cost of purchasing diesel fuel for the biogas CHP system ($)
C_{BGCHP}^{Esell}	Benefit of selling excess electricity to the grid for the biogas CHP system ($)
TC	Life time of conventional system (year)
TB	Life time of biogas CHP system (year)
EAi	Monthly electricity demand of animal farm in ith month (kWh)
P_e	Utility electricity price ($/kWh)
GOi	Animal farm's monthly demand of diesel fuel in ith month for conventional system (Liter)
P_{GO}	Diesel fuel price ($/Liter)
Fueli	Monthly required diesel fuel in ith month for Biogas CHP system (Liter)
P_{Esell}	Electricity buyback price ($/kWh)
$E_{buy}i$	Electricity that should be bought for ith month (kWh)
$E_{sell}i$	Excess electricity which is sold to the grid for ith month (kWh)
CSaving	Energy cost saving ($)
Payback	Period of payback (year)
I	Interest rate (%)
CER_{elect}	Carbon dioxide equivalent for electricity generation (g/kWh)
CER_{go}	Carbon dioxide equivalent for diesel fuel burning (g/Liter)
CER_{BG}	Carbon dioxide equivalent for biogas (g/Nm^3)
EF_{CH4}	Fraction of CH_4 produced and leaked from the digester (t CH_4 leaked/t CH_4 produced)
ρ_{CH4}	Methane density (t CH_4/Nm^3 CH_4)

1.1. The biogas production

Biogas can be used to generate electricity and heat simultaneously in a CHP plant. Anaerobic digestion can improve the energy supply security as well as help reduce greenhouse gas (GHG) emissions [5]. Anaerobic digestion use agricultural waste and convert it into both energy and fertilizers [5].

As noted before, biogas principally consists of methane (CH_4) and carbon dioxide (CO_2). The amount of methane produced by processing the animal manure varies, but usually is in the range of 45%–60% [6].

Biogas can be produced by processing the cow manure with an anaerobic digester, which provides a prime opportunity for cogeneration of heat and power to supply site energy demands and/or energy exports. The main differences between the technologies available for converting organic wastes to biogas are related to the cost and construction effort, the required land and the ability to handle feed stocks with different dry matter concentrations [7].

One of the most important issues in the construction of biogas plants is biogas producing rate. Considering that one ton of cow manure gives 25Nm^3 of biogas [8], the mentioned farm has a potential of producing about 53,910 Nm^3/month of biogas.

1.2. Incentive schemes for biogas CHP system in different countries

Many countries and governments have incentive schemes for renewable energies, such as biomass, wind, hydro, solar, and geothermal energies. Taxes and incentive schemes for biogas are planned to help individual investors, energy companies and other entities. In Table 1 a summary of the incentive schemes applied for biogas renewable energy in different countries is shown. There are also incentive schemes for biogas fuel in Iran. The tariff of purchasing electricity from biogas CHP plants is higher than the tariff of purchasing electricity from some other renewable power plants, such as the plants of wind power, hydropower and expansion turbines.

1.3. Internal combustion engine driven CHP system

The biogas produced from animal manure using an anaerobic digester, can be used in various applications. One of the most