Techno-Economic Analysis of a Grid-Connected Hybrid Biogas/Photovoltaic Power Generation System in the Mediterranean Region

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The European Conference on Sustainability, Energy & the Environment 2016
Official Conference Proceedings

Abstract
Depletion of fossil fuels and oncoming impacts of global warming reveal the vitality of utilizing renewable power generation systems for future generations of humanity. Investing in those systems also has several incentives in Europe for domestic equipment usage or selling produced electricity to the grid with advantageous tariffs in recent years. Reciprocating internal combustion engine based biogas cogeneration provides simultaneous heat and electricity with respect to a single fuel input that is obtained by the anaerobic digestion of renewable energy resources such as animal manures and regenerative raw materials. A biogas cogeneration plant with a photovoltaic (PV) system that transforms inexhaustible sunlight into electricity is an energy efficient and reliable alternative in order to produce heat and electrical energy at the same time for both on-grid systems in urban areas and off-grid systems in rural areas.

In this study, techno-economic analysis of a grid-connected hybrid biogas/PV power generation system settled in the Mediterranean Region is performed by investigating the scenario of selling the produced electricity to the national grid with the advantageous tariff price and evaluating heat energy within the plant.

Keywords: Hybrid, Biogas, Cogeneration, Photovoltaic, Power Generation.

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Introduction

According to predictions, by 2050s crude oil reserves will exhaust. By 2120s natural gas reserves and by 2220s coal reserves will also be exploited. Therefore, there are some about 34 years to replace oil by other energy carrier (Chasnyk et al., 2015). Recent years, energy production technologies based on renewable resources are prominent depending upon the depletion of fossil fuels (Zor, 2015). From all the renewable energy sources, the most promising is the solar energy which the most powerful and biomass energy that is most stable (Chasnyk et al., 2015).

Manure and wastewater have been used for energy purposes for millennia, with the earliest records of biogas utilization dating back to about 2000 years ago in Asia. By the 1800s, China and India burned biogas for heating water. Improved technology boosted production before the First World War was already feeding bio-methane into the gas distribution network in the 1920s. Since 1949, compressed biogas is being used as car fuel. After the Second World War, comparatively cheap oil made biogas unprofitable and many plants were closed down until the oil crisis in the early 1970s. As oil got costlier in the aftermath, biogas for heating, electricity or cogeneration became popular and production started to grow again. Energy production systems from biogas, which is the one of the most important renewable energy technologies, will have a worldwide installed capacity rating of 22 GW by 2025 (Mohammadi Maganaki et al., 2013).

Biogas is a flammable gas that is the main product of biodegradation of organic substances in an anaerobic environment (Toma et al., 2012). In biogas production process, organic matters such as animal manures or human waste, raw materials, and biomass, and solid wastes such as sewage. Biogas is mainly composed by 35% of carbon dioxide (CO_2) and 60% of methane (CH_4) that is a greenhouse gas with global warming potential 20 times greater when compared to carbon dioxide and, therefore, its emission to the atmosphere should be avoided. 5% of other gases like nitrogen (N_2), hydrogen (H_2), ammonia (NH_3), hydrogen sulphide (H_2S), carbon monoxide (CO) and volatile amines (Garcilasso et al., 2011).

Biogas is created by the digestion or fermentation of organic materials. The basic material is often slurry or solid manure. Regenerative raw materials or waste from the food industry are generally used as cofermentates. 50 – 70 % of the gas produced this way is composed of the high-quality fuel methane. A multiplicity of organic materials can be used in a biogas plant. Some systems run entirely on slurry and solid manure, while others exclusively use regenerative raw materials. Frequently, a mixture of materials is used. The principle of a cogeneration system based on biogas is demonstrated in Figure 1 (MTU, 2016). The biogas is used to generate power in a manner that is both economical and saves resources. The power produced can either be used to supply the operator's own requirements, or it can be fed into the public power grid (MTU, 2016).

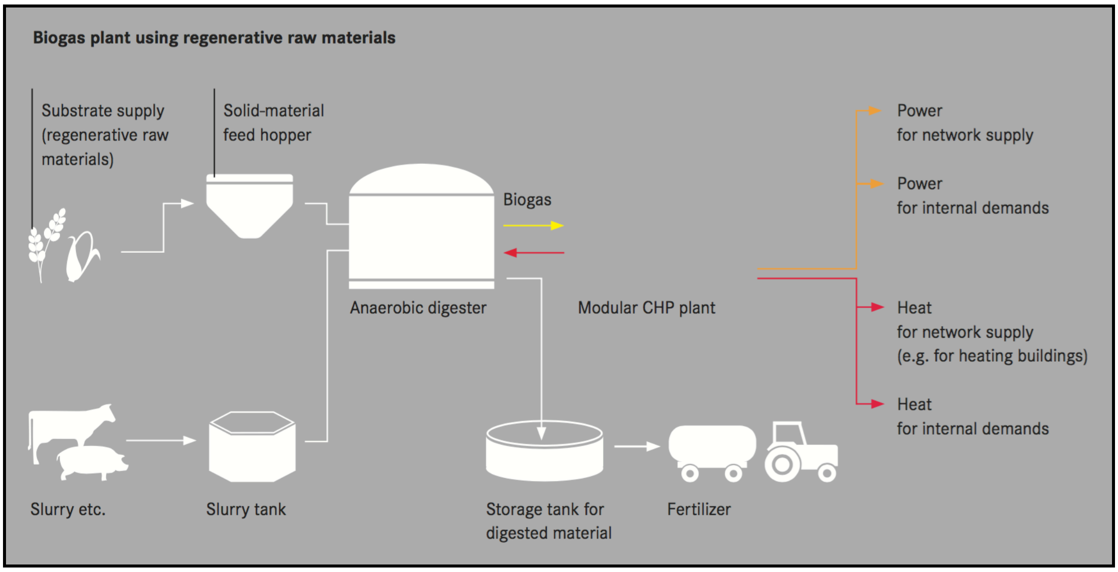

Figure 1: The principle of a cogeneration system based on biogas from regenerative raw materials and animal waste.

Electrical, heat, and the overall efficiencies of a 999kW, 400V, 50Hz biogas based cogeneration plant operating with animal manures are shown in Figure 2. While calculating efficiencies, whole electricity that is generated in the plant is assumed to be sold to the grid and heat outputs (heat recovery from exhaust gas, high-temperature (HT) circuit, and low-temperature (LT) circuit) produced by heat recovery is assumed to utilize in the biogas complex totally. Electrical output is 999kW, heat outputs are 1075kW (heat recovery from exhaust gas and HT circuit) and 86kW (LT circuit) respectively. Energy input of the biogas cogeneration plant is 2407kW. Methane content of the biogas is at least 60% of its volume (MTU Specification, 2016).

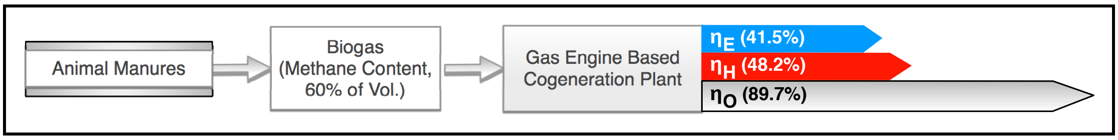

Figure 2: Efficiencies of GR999B5-12V4000L62 Biogas Cogeneration Plant (MTU Specification, 2016).

In Turkey, biogas based cogeneration plants are encouraged to sell electricity to the grid with an advantageous tariff price shown in Table 1 (Zor et al., 2015).

Table 1: Applicable tariff prices for power plants generating electricity based on renewable energy sources (RES) in Turkey

Type of Plants	Applicable Tariff Prices (¢/kWh)
Hydraulic Power Plant	7.3
Wind Power Plant	7.3
Geothermal Power Plant	10.5
Biomass Power Plant (incl. Landfill gas)	13.3
Solar Power Plant	13.3

13.3 ¢/kWh, tariff price can be increased by using fluidized bed boiler, gasification and gas purification group, internal combustion engine (ICE), generator and power electronics, and cogeneration system manufactured domestically as demonstrated in Table 2 (Zor et al., 2015).

Table 2: Extra addition for ICE based cogeneration plants contain domestically manufactured equipment.

Domestically Manufactured Equipment	Extra Additions to Applicable Tariff Prices (¢/kWh)
Fluidized Bed Boiler	0.8
Gasification and Gas Purification Group	0.6
Internal Combustion Engine (ICE)	2.0
Generator and Power Electronics	0.5
Cogeneration System	0.4

In Turkey, 20% of cogeneration and trigeneration plants use biogas as input fuel. Regional capacities of biogas cogeneration and trigeneration plants can be sorted such that Marmara Region 83.305MW, Central Anatolia Region 64.948MW, Mediterranean Region 23.593MW, Southeast Anatolia Region 8.966MW, Black Sea Region 7.731MW, Aegean Region 6.701MW, and Eastern Anatolia Region 4.421MW by January 2015 as shown in Figure 3 (Zor, 2015).

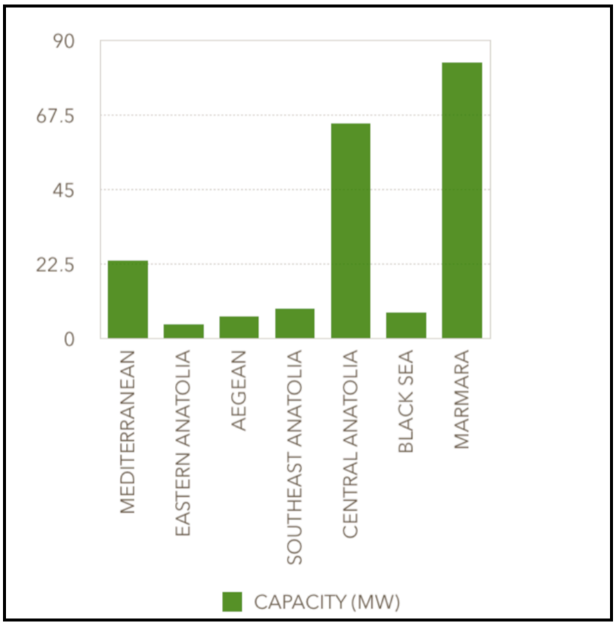

Figure 3: Regional capacities of biogas cogeneration and trigeneration plants in Turkey.

PV is a technology that directly converts solar radiation into electricity by using solar cells. These cells absorb photons and due to the photoelectric effect, electrons are liberated from p-n junction. These free electrons are forced to fill the holes on a path and an electric current occurs. Because of this operation principle, PV systems have so many advantages like no noise, almost maintenance free, inexhaustible, sustainable, abundant and environmentally friendly. However, these systems suffer from the initial cost of purchasing and installing PV modules. Furthermore, being inefficiency, which dramatically affects the payback period of the plant, is the most significant problem of these systems (Çelik, 2015).

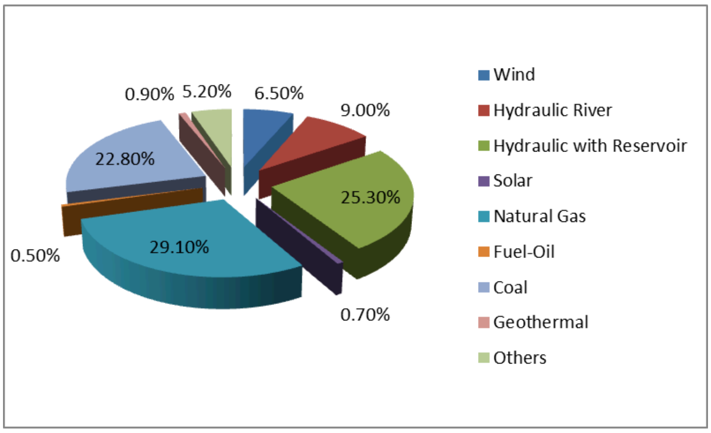

Figure 4: Total installed power ratings according to source usage in Turkey (EI, 2016).

According to the International Energy Agency's 2016 report, solar energy is the world's fastest-growing form of renewable energy, with net solar generation increasing by an average of 8.3% per year. It is also estimated that the solar generation grows by 15.7% per year on average from 2012 to 2040 (EIA, 2016). Despite being abundant in terms of renewable energy sources, in Turkey these sources are not utilized effectively. When Figure 4 is investigated, it can be seen that the distributions of the resources in terms of the installed power ratings are not in the desired level. In Turkey, total installed solar power reached to 248.8MW at the end of 2015 and it is aimed to attain at least 3GW of PV installed power until the 2023 (YEGM, 2016).

In the following sections, overview of the study area where hybrid power generation system is planned to install, proposed operational scenario of the system, discussions and results of the techno-economic analysis are presented sequentially.

Overview of Study Area

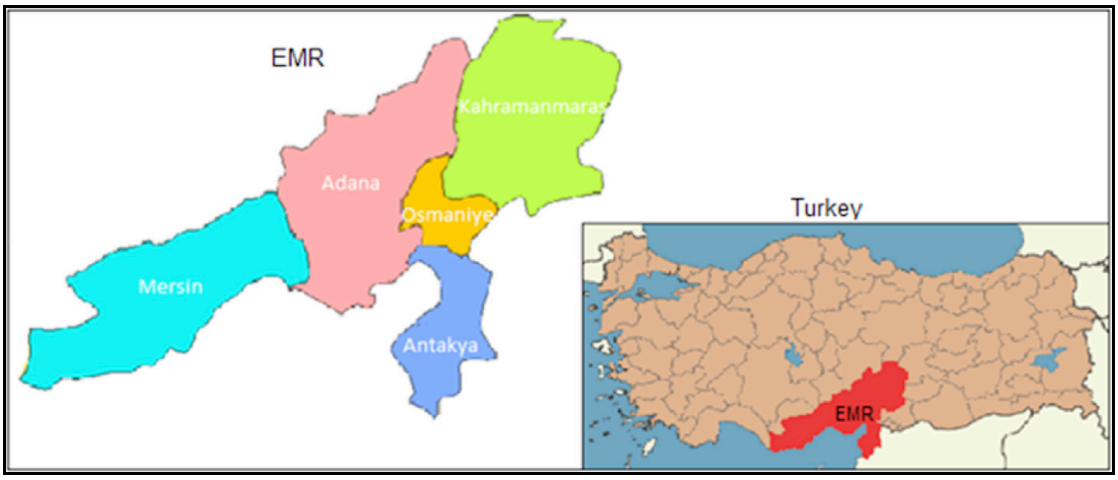

Figure 5: Map of the study area (Çelik et al., 2016).

The Mediterranean Region is one of the seven main regions in Turkey. Adana is the most populated province in the Eastern Mediterranean Region (EMR) that is under the Mediterranean Climate. The Mediterranean coasts have cool, rainy winters and hot, moderately dry summers. Geographical parameters belong to Adana is shown in Table 3 (Çelik et al., 2016).

Table 3: Geographical parameters of the province in the Mediterranean Region.

Province	Longitude (E)	Latitude (N)	Altitude (m)	Daily Average Sunshine Duration (h)	Daily Average Air Temperature (ºC)
Adana	35º19′	37º0′	27	7.34	19.29

Hybrid biogas/PV power generation system is planned to be situated in a dairy cow farm contains 7,500 cows. Manures of the cows will feed a biogas degradation system with an anaerobic digester unit, and the obtained biogas will utilize as input fuel of the cogeneration plant. On the roof the cogeneration plant building, 60 PV modules, each is 250W$_p$, will be settled by a tilt of 30º as demonstrated in Figure 6.

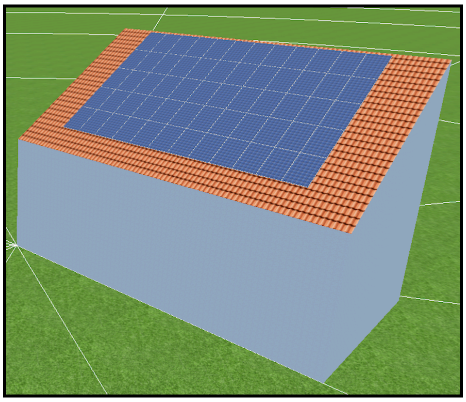

Figure 6: Biogas cogeneration plant building with 60 PV modules on the roof (PV*SOL, 2016).

Proposed Scenario

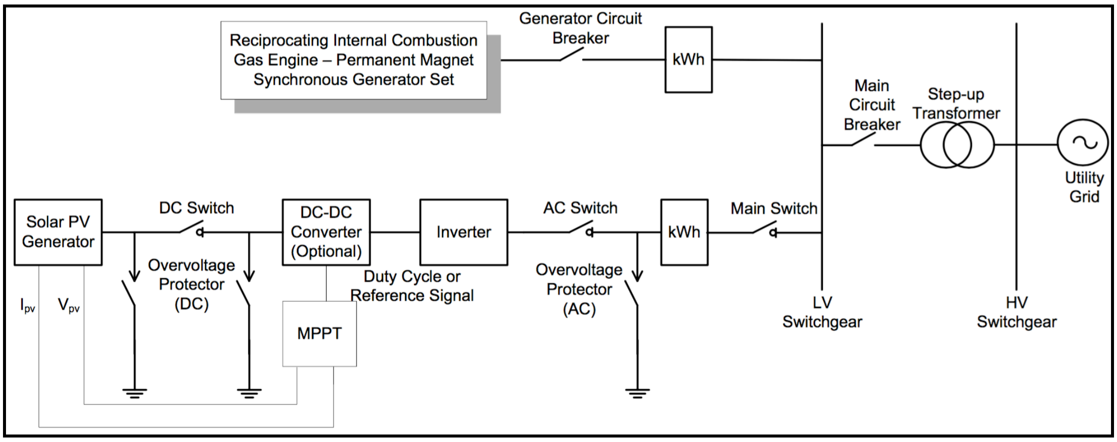

Figure 7: The proposed scenario for the hybrid biogas/PV power generation system.

In the proposed scenario, as shown in Figure 7, biogas cogeneration plant produces electrical energy and sells all of the energy to the grid with a 13.3¢/kWh tariff price via a 0.4/31.5kV step-up transformer. Similarly, PV plant generates electricity and sells all of the energy to the grid with the same tariff price via the same transformer.

Internal electricity consumption of the whole farm (dairy farm, houses, hybrid power generation system, and the biodegradation complex) is provided by purchasing electricity with a low tariff price from the local grid.

Heat outputs of the biogas cogeneration plant are utilized in the biodegradation complex, houses, kitchens, and baths.

According to GE Jenbacher, manures of 7200 dairy cows can feed in an anaerobic digester, which also feeds in a 1MW biogas cogeneration plant. As biogas cogeneration plant, a GR999B5-12V4000L62 biogas engine-alternator set is planned to use. The plant can generate 999kW electric power at full load (MTU Specification, 2016). As PV plant, 60 modules of SF(P)60 are utilized. The PV plant will have total peak capacity rating of 15kW (Solarfield, 2016). For the hybrid biogas/PV power generation system, investment and maintenance costs are offered by MTU Onsite Energy and Solarfield.

Discussions and Results of the Techno-Economic Analysis

Table 4: Financial viability of the proposed scenario.

	Biogas Cogeneration	PV	Hybrid
Investment Cost ($)	1,450,000	36,000	1,486,000
Annual Revenue ($)	700,000	3,640	703,640
Payback Period (year)	2.07	9.89	2.11

For PV plant modelling, calculations and feasibility analyses, PV*SOL Expert 6.0 software program is used (PV*SOL, 2016). Savings for selling electricity to the grid is taken into account in the PV*SOL. Expenses for maintenance and cleaning of modules are subtracted from the annual revenue of the PV plant.

For biogas cogeneration plant and degradation complex, heat outputs are utilized in the complex, hence there’s no savings for heat recovery from the plant. Savings for selling electricity to the grid is taken into account in the analysis. Expenses for internal electricity consumption, annual chemical desulphurization, service and spare parts for maintenance, and operators’ salaries are considered and also subtracted from the annual revenue of the biogas cogeneration plant.

Consequently, a hybrid 999kW biogas/15kW roof-mounted PV plant power generation system which is settled in a dairy cow farm complex of 7,500 cows in Adana in the Mediterranean Region has a payback period of 2.11 years, and installation of such a system is also reliable, financially feasible and ecologically sustainable.

Conclusions

Extinction of fossil fuels and impacts of global warming indicates the importance of using renewable power generation systems for future generations. Investing in those systems also has several incentives in Europe for domestic equipment usage or selling produced electricity to the grid with advantageous tariffs in recent years. In Turkey, it is also advantageous because of the fact that tariff prices for selling the electricity which is produced by renewable power generation is higher than the grid's tariff price.

Engine based biogas cogeneration provides heat and electricity at the same time according to a single fuel input which is obtained by the anaerobic digestion of renewable energy resources such as animal manures. A biogas cogeneration plant with a PV system that converts abundant sunlight into electricity is an energy efficient and reliable option for producing heat and electrical energy simultaneously.

For a hybrid biogas/PV power generation system in Turkey, investment costs are higher, but payback periods are about 2-3 years especially for systems over 500kW for the biogas part. Therefore, installing those hybrid plants seems to be very beneficial with actual incentives in the current legislation.

In this paper, techno-economic analysis of a grid-connected hybrid biogas/PV power generation system planned to settle in Adana in the Mediterranean Region is investigated by performing the scenario of selling the produced electricity to the national grid with the advantageous tariff price and evaluating heat energy within the plant.

Acknowledgements

The authors would like to acknowledge the Scientific and Technological Research Council of Turkey (TÜBİTAK) (Project No. 113E769 and 114Y391) for full financial support.

The authors are also grateful for research and financial support provided by the Scientific Research Project Unit of Çukurova University (Project No. FYL-2014-2351 and FYL-2014-3485).

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