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Energy Saving and GHG Emission Reduction in a Micro-CCHP System by Use of Solar Energy

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***Abstract* – In this work, the reduction of greenhouse gas emission, and the energy saving by integrating solar collectors and photovoltaic panels in a Stirling engine based micro-combined cooling, heating and power (mCCHP) system are studied. The mCCHP system consists of a natural gas Stirling CHP and an adsorber chiller. When the thermal outputs of the Stirling CHP and solar collectors are not sufficient to cover the heat demand for domestic hot water (DHW), heating/cooling, an auxiliary heating boiler starts to operate. The energy saving by using solar energy varies from 13.35% in December to 59.62% in April, in the case of solar collectors usage and from 7.47% in December to 28.27% in July, in the case of photovoltaic panels usage. By using solar energy the annual GHG emission decreases by 31.98% and the fuel cost reduction varies from 12.73% in December to 49.78% in June.**

***Keywords* – micro CCHP, biomass heating boiler, solar energy, greenhouse gas emission, energy saving**

I. Introduction

One of the 2020 Europe strategies known as "A resource efficient Europe" is to achieve the 20-20-20 targets, that means: reduction in EU greenhouse gases emissions of at least 20% below 1990 levels; 20% of EU energy consumption to come from renewable resources; 20% reduction in primary energy use to be achieved by improving energy efficiency [1].

Since buildings currently account for around 40% of total energy consumption in the EU, there is an important potential to reduce the greenhouse gas emissions through a more efficient use of energy and the use of energy from renewable sources in buildings. The Energy Performance of Buildings Directive 2010/31/EU (EPBD) promotes the improvement of the energy performance of buildings within the EU, taking into account outdoor climatic and local conditions, as well as indoor climate requirements and cost-effectiveness, and requires Member States to ensure that all new buildings will be so-called "nearly zero-energy buildings" by 2020. The EU also promotes cogeneration based on a useful heat demand [2]. Besides the cogeneration systems, in the residential sector there is a growing interest in energy systems that involve the integration of renewable and conventional energy sources to produce electricity, heat and cooling (CCHP systems) simultaneously. In CCHP systems, the waste heat from the prime mover is used to satisfy the thermal demand (heating and cooling) achieving an energy efficiency level of around 80%.

Due to the increasing price and low quality of centralized heating, many users are looking for more convenient options. To satisfy the users' requirements, the market offers a variety of small and micro energy conversion plants that deliver power, heating and cooling with lower greenhouse gas (GHG) emissions and high energy efficiency.

The use of a CCHP system for a remote residence is the best solution to satisfy the electricity and heat demands. In a traditional power plant, in addition to the large energy loss through the discharge of waste heat, energy losses occur in the transmission and distribution of electricity to individual users [3]. The micro CCHP systems are typically designed at less than 30kW electric to produce both electricity and useable thermal energy onsite or near site, reducing the energy losses that occur during transmission and distribution.

As prime mover for the micro CCHP systems can be used internal combustion engines, gas turbines, steam turbines, organic Rankine engines, Stirling engines or fuel cells. The most commonly used prime movers for medium-scale (100–5000 kW) applications and appropriate for commercial buildings are reciprocate internal combustion engines, because they have an almost flat efficiency curve above 30% of the nominal electrical power [4]. The advantages of using Stirling engines as the prime mover include higher energy efficiency, lower pollutant emissions and noise levels compared to internal combustion engines.

There are a lot of studies on the CCHP systems focused on the design, energy, environmental and economical analyses and optimization [5]-[12].

A mCCHP system was designed and built at "Dunarea de Jos" University of Galati within the framework of the project "Integrated micro CCHP –Stirling engine based on renewable energy sources for the isolated residential consumers from the South-East region of Romania (m-CCHP-SE)", granted by the EEA Financial Mechanism. The system was designed to operate only with renewable energy, biogas for Stirling engine and wood pellets for the auxiliary heating boiler. At the moment the system works on natural gas due to the unavailability of a biogas source. In order to reduce the fuel consumption and therefore the greenhouse gas emission photovoltaic panels and evacuated tube collectors were integrated in the system. This study deals with the environmental and economic analyses based on the energetic model of the mCCHP system. In the study, the operation of the prime mover (Stirling engine) matching the electric load was considered.

II. System Description

The studied mCCHP system consists of a natural gas Stirling CHP, an adsorber chiller, a hot water storage tank, a cold water storage tank, an auxiliary heating boiler, solar collectors, photovoltaic panels, two cooling towers and pumps to circulate the fluids (Fig. 1).

The characteristics of the main components of the system are given in Table I. The residential building equipped with the mCCHP system is 270 m^2 and was designed to correspond to the A energetic class with the following average yearly specific consumptions: electricity 45 kWh/m^2; heating 70kWh/m^2, cooling 20 kWh/m^2 and domestic hot water 15kWh/m^2.

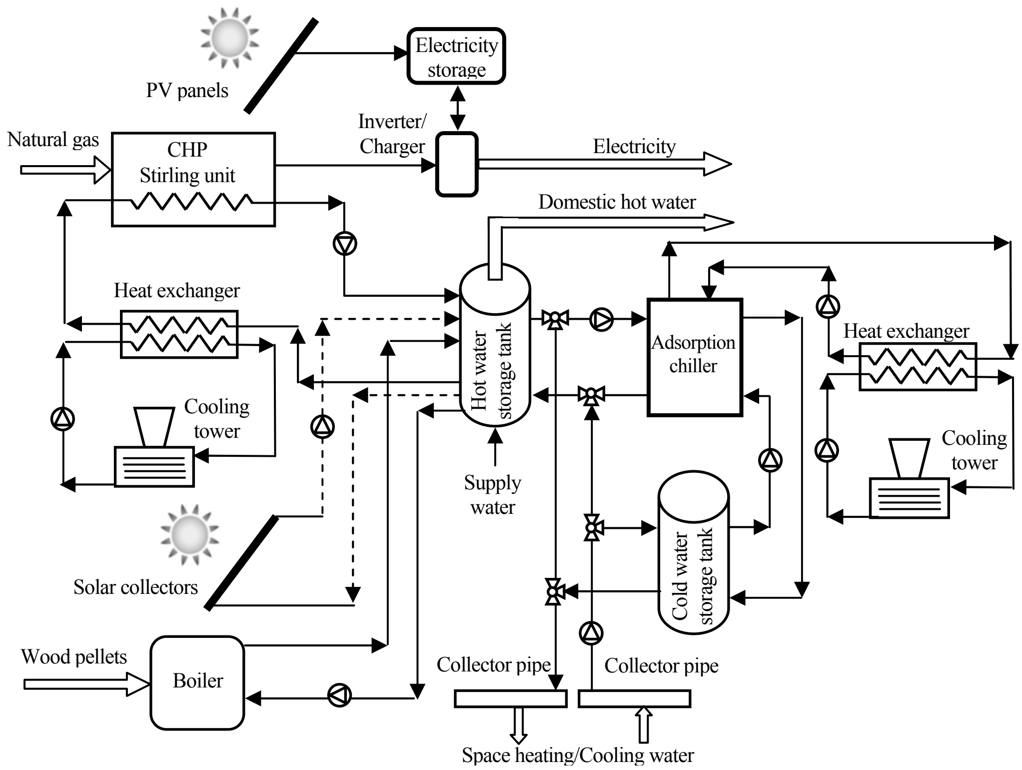

Fig. 1. Schematic diagram of the mCCHP system.

TABLE I

SYSTEM CHARACTERISTICS

Stirling CHP (SOLO Stirling 161)	
Fuel type	natural gas
Power output	(1.1–8.9) kW
Heat output	(6-24.8) kW
Heat to electricity output ratio (η)	3
Electrical efficiency (η_{el})	26.8%
Overall efficiency	98.5%
Hot water temperature	(70-85)°C
Inlet water temperature	60°C
Auxiliary heating boiler	
Fuel type	biomass pellets
Heat output	30 kW
Hot water temperature	95°C
Water pressure	3 bar
Thermal efficiency (η_b)	0.87
Photovoltaic panels	
PV module type	mono Si
Nominal PV efficiency	14,0%
PV temperature coefficient	0,40%
Overall PV system efficiency (η_{pvp})	12,5%
Total aperture area (A_{pvp})	10 m^2
Adsorption chiller (SorTech AG ACS15)	
Cooling capacity	(10-23) kW
Coefficient of performance (COP)	0,6
Driving heat circuit	(55-95)°C
Chilled water circuit	(6-20)°C
Heat rejection circuit	(22-37)°C
Power consumption	14 W
Solar collectors	
Type	vacuum tube
Total aperture area (A_{sc})	17.2 m^2

III. POWER, HEATING AND COOLING CONSUMPTIONS

There are many calculation methods used to estimate the energy requirements of buildings for electricity, domestic hot water, space heating and cooling. For EU Member States the Energy Performance of the Buildings Directive 2010/31/EU (EPBD) lays down requirements as regards the common general framework for a methodology to calculate the integrated energy performance of buildings and building units.

The calculation methods are divided into steady state calculation methods, which assume steady indoor and outdoor conditions for the calculation of the heat gains and losses in the building and dynamic methods which take into account climate variations and the effect of heat absorption and release inside the building [13].

One of the calculation methods which is applied the most due to its simplicity is the degree-days method to estimate the heating and cooling loads in buildings in winter and summer periods.

According to this method, the monthly heating and cooling loads are given by the following equations [13] and [14]:

- monthly heating load:

$$Q_h = \frac{24 \cdot U \cdot A \cdot HDD}{\eta_h} \text{ [kWh]} \quad (1)$$

- monthly cooling load:

$$Q_c = \frac{24 \cdot U \cdot A \cdot CDD}{\eta_c} \text{ [kWh]} \quad (2)$$

where: A – total surface of walls, ceiling and floor, through which the energy is lost, [m^2]; U - overall coefficient of heat losses of the building, [kW/(m^2·°C)]; HDD – monthly number of degree-days for heating, [°C·day]; CDD – monthly number of degree-days for cooling, [°C·day]; η_h - efficiency of the heating system; η_c - efficiency of the cooling system.

The daily necessity of heat for domestic hot water can be estimated by the equation:

$$Q_{dhw} = c_p \frac{G_{hw}^N \cdot N}{24 \cdot 3600}(t_{wh} - t_{wc}) \text{ [kWh]} \quad (3)$$

where: c_p – specific heat of water at constant pressure, [kJ/(kg·°C)]; G_{hw}^N - daily consumption of hot water per person, [l/person]; N - number of people in the building; t_{wh}, t_{wc} – temperatures of delivered hot water and water that is heated, respectively, [°C].

The monthly amount of electricity generated by Stirling CHP can be rewritten as:

$$P_{St} = \frac{\eta_{el} \cdot F_S \cdot LHV}{3600} \text{ [kWh]} \quad (4)$$

where: F_S – monthly fuel consumption of Stirling CHP, [Nm^3]; η_{el} – electrical efficiency of Stirling CHP.

The monthly amount of electricity produced by the photovoltaic panels can be calculated as the following:

$$P_{pvp} = A_{pvp} \cdot G_T \cdot \eta_{pvp} \text{ [kWh]} \quad (5)$$

where: A_{pvp} – total aperture area of photovoltaic panels, [m^2]; G_T – monthly average radiation in plane of PVP array, [kWh/m^2]; η_{pvp} - overall PV system efficiency;

The monthly amount of heat produced by a Stirling engine is given by the equation:

$$Q_{St} = \eta \cdot P_{St} \text{ [kWh]} \quad (6)$$

where: η - heat to electricity output ratio of Stirling engine.

The monthly amount of heat produced by the solar collectors is:

$$Q_{sc} = \eta_{sc} \cdot A_{sc} \cdot G_T \text{ [kWh]} \quad (7)$$

where: A_{SC} – total aperture area of solar collectors, [m^2]; η_{SC} – solar collector thermal efficiency. It is estimated by the following equation:

$$\eta_{sc} = \eta_0 - a_1 \frac{T_m - T_a}{G} - a_2 \frac{(T_m - T_a)^2}{G} \quad (8)$$

where: G–total solar radiation in plane of solar collector, [kW/m^2]; η_0–optical efficiency (η_0 = 0.809); a_1, a_2-thermal loss correction values (a_1= 1.37 W/(m^2 K); a_2=0.0068W/(m^{2}K^2)); T_m – average collector temperature; T_a – ambient temperature.

The monthly amount of heat produced by the heating boiler can be expressed as follows:

$$Q_b = \frac{\eta_b \cdot F_b \cdot LHV}{3600} \text{ [kWh]} \quad (9)$$

where: η_b – boiler thermal efficiency; F_b – monthly fuel consumption of the heating boiler, [kg].

Using the RETscreen 4 software [15] there were found, for Galati as location, the monthly average daily solar radiation in plane of PV panels and solar collectors (kWh/m²/d), the monthly number of degree-days for heating and degree-days for cooling (Table II). With this data there can be calculated the monthly heating and cooling demands, the monthly amount of electricity produced by PV panels and heat produced by solar collectors. The results are shown in Figure 2 and Table III. The monthly total electricity demand (lighting, building and mCCHP consumption) varies slightly having an average value of 983kWh which corresponds to the specific consumption of 43.68 kWh/m^2. The monthly domestic hot water demand was considered to be constant (337.5 kWh).

TABLE II

WEATHER DATA FOR GALATI AS LOCATION [15]

Month	Monthly average temperature [°C]	Monthly average daily radiation in plane of PVP [kWh/m²·d]	Monthly degree-days for heating [°C·d]	Monthly degree-days for cooling [°C·d]
January	-1.7	2.77	611	0
February	-0.6	3.65	521	0
March	5.0	4.34	403	0
April	11.1	5.24	207	33
May	16.7	5.53	40	208
June	20.0	5.87	0	300
July	21.7	5.91	0	363
August	21.7	5.79	0	363
September	17.8	5.26	6	234
October	11.7	4.51	195	53
November	5.0	2.98	390	0
December	0.6	2.29	539	0

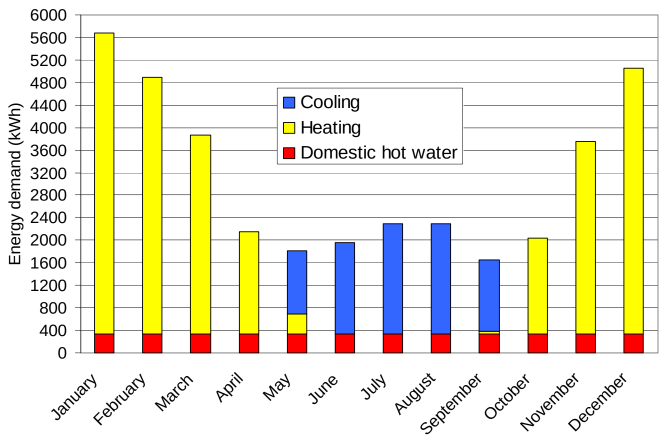

Fig. 2. The monthly demands for heating, domestic hot water and cooling.

In April, May, September and October when neither heating nor cooling is necessary, the amount of heat produced by the solar collector and the Stirling CHP exceeds the total heat demand and a part of the heat generated by the Stirling CHP is rejected in a cooling tower.

TABLE III
MONTHLY ENERGY GENERATED BY PV PANELS AND SOLAR COLLECTORS

Month	Total electricity demand [kWh]	Total heat demand [kWh]	Electricity gained by PV panels [kWh]	Heat gained by solar collectors [kWh]
January	1188	5682.53	107.34	815.77
February	1134	4895.21	127.75	970.90
March	999	3862.94	168.18	1278.13
April	891	2504.74	196.50	1493.40
May	810	2933.82	214.29	1628.59
June	810	3577.50	220.13	1672.95
July	810	4257.90	229.01	1740.50
August	810	4257.90	224.36	1705.16
September	945	2917.19	197.25	1499.10
October	1080	2615.76	174.76	1328.20
November	1134	3749.22	111.75	849.30
December	1188	5052.67	88.74	674.41

IV. ENERGY SAVING AND GREENHOUSE GAS EMISSION ASSESSMENT

The use of solar energy to generate electricity and heat can save enough Stirling CHP and boiler power to cover the costs of solar collectors and photovoltaic panels in a few years. The Stirling engine uses natural gas with the lower heating value of 35500 kJ/Nm^3 and the heating boiler uses wood pellets with the lower heating value of 18000 kJ/kg. There are many works on the calculation of energy saving by using solar energy in heating and cooling systems [15], [16] and [17]. In this paper the percentages of energy saving by using solar collectors and photovoltaic panels are expressed as follows:

- energy saved by solar collectors:

$$ES_{SC} = \frac{Q_{SC}}{Q_{hd}} 100 [\%] \tag{10}$$

- energy saved by photovoltaic panels:

$$ES_{pvp} = \frac{P_{pvp}}{P_{ed}} 100 [\%] \tag{11}$$

where: Q_{hd} – total heat demand, [kWh]; P_{ed} – total electricity demand, [kWh].

By applying equations (10) and (11) to the studied system, the results given in Figure 3 are obtained. It can be observed that the energy saved by the photovoltaic panels varies from 7.47% in December to 28.27% in July and the energy saved by the solar collector varies from 13.35% in December to 59.62% in April.

There are many approaches to estimating the greenhouse gas emissions reduction from the energy systems [5], [6], [7], [15] and [18]. Using the GHG emission factors (Table IV) and knowing the energy consumptions of the mCCHP system in both cases with and without use of solar energy, the reduction of GHG emission can be calculated. The result of these calculations is shown in Figure 4. The total GHG amount in CO_2 equivalent saved through use of solar energy in the mCCHP system in one year is about 4709 kg CO_2, which means a reduction by 31.98%.

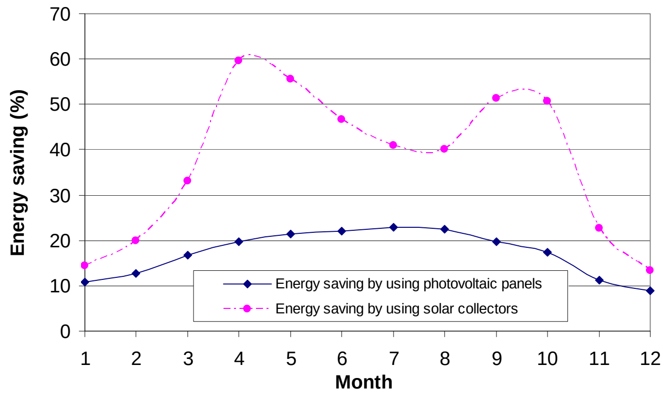

Fig. 3. Energy saving by using solar energy in the mCCHP system.

TABLE IV
GHG EMISSION FACTORS [18]

Fuel type	CO_2 emission factor [kg/TJ]	CH_4 emission factor [kg/TJ]	N_2O emission factor [kg/TJ]	GHG emission factor [t_{CO2-eq}/kWh]
Biomass	0.0	0.3	4	0.027
Oil	74100	10	0.6	0.268
Natural gas	56100	5	0.1	0.202

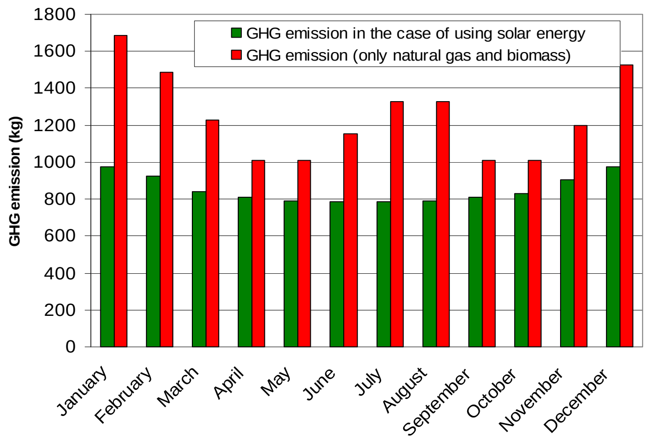

Fig. 4. GHG emissions of the mCCHP system.

The use of solar energy in the mCCHP system leads also to savings in fuel cost. Taking into account that in Romania the fuel costs are: 0.032 €/kWh for wood pellets and the 0.028 €/kWh for natural gas, the results of fuel cost reduction are shown in Figure 5. The fuel cost reduction varies from 12.73% in December to 49.78% in June. The total reduction of fuel cost is about 722 €/year. Considering a total cost of solar collectors and photovoltaic panels of 5000 € the results indicate that the capital cost can be recovered in less than 7 years.

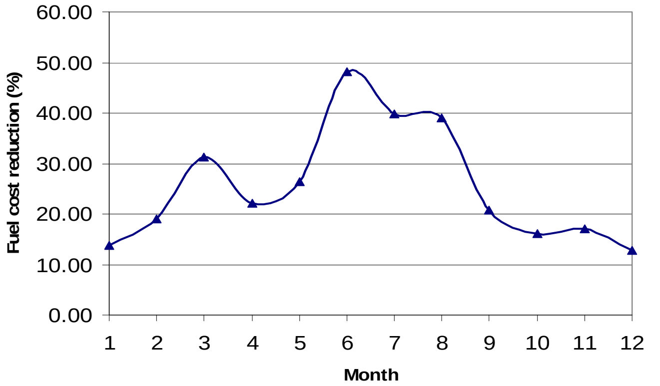

Fig. 5. Fuel cost reduction through use of solar energy.

V. Conclusions

The mCCHP system uses the primary energy more efficiently and economically than the traditional power plants and therefore it has lower greenhouse gas emission due to reductions in energy losses by transmission and distribution of energy to individual users and the use of renewable energy as a primary energy source.

In this paper a model was developed by using the technical characteristics of the system components and of the existing weather data to estimate the energy and carbon savings by using solar energy. Using the simplified approach, calcluations were made for the studied mCCHP system on: the energy saving, the GHG emission reduction and the fuel cost reduction obtained in a year by using solar energy. The total amount of energy saved is of 2060 $kW_{el}h$ and of 15656 kW_th. The reduction of GHG emission is of 4709 kg CO_{2-eq}. The reduction of fuel cost is of 722 €/year.

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