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FEASIBILITY ANALYSIS AND OPTIMIZATION OF GRID-CONNECTED MICROTURBINE/FUEL CELL/PV HYBRID ENERGY SYSTEM

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Abstract: In this paper, a grid-connected hybrid energy system consisting of microturbine, fuel cell, photovoltaic system and inverter is presented. The study is focused on determining the optimal configuration of the system, which will meet the electrical and thermal load, respecting the total net present cost. HOMER software is used to achieve this purpose. The emissions of pollutants are also analyzed.
Key words: hybrid energy system, microturbine, fuel cell, photovoltaics, optimal configuration, net present cost.

1. INTRODUCTION

Hybrid energy system may employ various combination of electrical and thermal generation components and storage technologies, to serve a nearby load. Such a system may be grid-connected or off-grid. Hybrid energy production from available renewable resources in combination with non-renewable power generation is considered as an economically viable and environmentally friendly solution.

The analysis and design of hybrid energy systems can be challenging, due to the large number of alternative technologies, the differences in technology costs and the uncertainty in key parameters. Renewable energy sources add further complexity because their power output may be intermittent, seasonal, and nondispatchable, and the renewable resources availability may be uncertain.

When designing hybrid energy system, off-grid or grid-connected, it is necessary to decide about the configuration of the projected system. This includes deciding on the following questions: what type of technologies will be used for energy generation? Which components will be part of the system? How many, what size and with what characteristics will be the used components?

Microturbines are small gas turbines and can be used in power-only generation or in combined heat and power (CHP) systems. The economics of microturbine power generation are enhanced by continuous base load operation and the effective use of the thermal energy contained in the exhaust gas [1]. Microturbines are well suited for a variety of distributed generation applications due to their flexibility in connection methods, ability to provide reliable power, and low-emissions profile. Fuel cells is another technology option which have the potential for clean and very efficient power generation, and can be one of the components in a hybrid energy systems.

HOMER is a software tool that can be used to analyze a grid-connected and off-grid hybrid energy systems serving electrical and thermal loads. A component that can be modeled, in this tool, is a part of a system that generates, stores or transmits electricity or thermal energy. The following components are included: wind turbines, photovoltaic system (PV), run-of-river hydro power plants, biomass power, reciprocating engine generators, microturbines, fuel cells, batteries, converters and hydrogen storage, etc. [2]. HOMER's optimization and sensitivity analysis algorithms make it easier to evaluate the many possible system configurations.

In this paper, a grid-connected hybrid energy system to supply the electrical and thermal load demand is considered. The system consists of microturbine, fuel cell, photovoltaic system and inverter, and is modelled in HOMER. The objective of this study is to determine the optimal configuration of the system that will meet the needs of consumers, respecting the total net present costs. Also, the emissions of pollutants are analyzed for different system configurations. HOMER software is used to perform simulation, calculation and optimization [3].

2. RELATED WORK

Much research has been done regarding the hybrid energy systems. In [4], techno-economic performance of stand-alone electricity generation systems for off-grid communities located in different climatic areas of Peru was investigated. Seven scenarios, including different combinations of diesel generators, wind turbine units, and solar panels, were assessed. Optimal sizing of each configuration, which minimizes the corresponding net present cost (NPC), was determined and the achieved optimal systems were also evaluated considering other economic indices and their environmental performance.

The study, in [5], was developed to design a grid-connected hybrid energy systems including PV and fuel cells, and discuss the influence of the major types of PV tracking technique on technical and economic performance of the system. In the case study, the results show that the vertical single axis tracker was ranked 1st in terms of highest PV generation, penetration of renewable energy to the grid, lowest

CO_2 emission, highest energy sold to the grid and lowest purchased, and lowest NPC and levelized cost of energy. The authors in [6] investigated a wind turbine/PV/fuel cell hybrid power system using HOMER software and an m-file MATLAB code for the clonal selection algorithm optimization method. The optimal results of the two methods using the same load data and weather conditions have been illustrated and compared to each other.

The authors in [7] presented the optimal design of a stand-alone hybrid photovoltaic and fuel cell power system without battery storage to supply the electrical load demand of the city of Brest, Western Brittany in France. The proposed optimal design study was focused on economical performance and was mainly based on the loss of the power supply probability concept. In [8], the authors proposed an optimization method to manage the optimal energy management of the PV–wind–diesel–battery hybrid system with respect to both economic benefits and its reliability. The Dynamic Programming approach was used to establish the optimal schedule of power sources. This method can minimize the operation cost of the hybrid system and CO2 emission while satisfying the technical conditions such as reliability, safety, etc. in scenarios with the different initial states of charge.

In [9] paper presented dynamic behavior and simulation results in a stand-alone hybrid power generation system of wind turbine, microturbine, solar array and battery storage. At first, a developed Lyapunov model reference adaptive feedback linearization method accompanied by an indirect space vector control is applied for extraction of maximum energy from a variable speed wind power generation system. Then, a fuzzy logic controller is designed for the mentioned purpose and its performance is compared with the proposed adaptive controller. For meeting more load demands, the solar array is integrated with the wind turbine. In addition, the microturbine and the battery storage are combined with the wind and solar power generation system as a backup to satisfy the load demand under all conditions. A research carried by [10] present a techno-economic feasibility study of hybrid energy systems (PV/wind turbine/diesel system with storage batteries) for electricity generation. The incorporation of storage units also reduced the net present cost, excess energy fraction and CO_2 emission. They found out that the use of hybrid energy systems in such locations improved the standard of living and economic activities of the rural populace.

The authors in [11] investigated several hybrid renewable energy system combinations of solar, wind and energy storage free of diesel generators to supply energy for remote communities. The study showed that the wind turbine operations range must be considered. Increasing the wind turbine fraction could also lead to significantly lower costs as well as the PV solar cell number and number of batteries. In [12], the authors proposed a two-step methodology to optimize and analyze a PV/wind/battery/diesel hybrid energy system to meet the power demand of Fanisau, a remote and off-grid village in northern Nigeria. In the first step, the MATLAB was used to run simulations and optimize the system via the genetic algorithm with a time interval of 1h over a year for the load demand and energy output. Then, techno-economic and emissions analysis was carried out in the second step to compare the obtained optimized system to the traditional modes of rural electrification in sub-Saharan Africa.

3. PROPOSED RESEARCH

In this paper, a grid-connected combined heat and power system consisting of microturbine (MT), fuel cell (FC), photovoltaic system and inverter is analyzed. Figure 1 presents the MT/FC/PV hybrid energy system that is modelled in HOMER software. The boiler is an idealized component that can serve un unlimited thermal load at only the cost of fuel. Waste heat recovered from a generator reduces the fuel consumption of the boiler. So, the boiler is treated as a backup source of heat that can serve any amount of thermal load whenever necessary.

Microturbine and fuel cell produce both electricity and heat, while photovoltaic system generates electricity. The objective of this study is to obtain the optimal configuration of the system, which should satisfy the given electrical and thermal load, respecting the total net present costs. In the paper the emissions of pollutants are also analyzed. For this purpose the software tool HOMER is used. Lifetime of the project is 25 years, while the interest rate is 6%.

In HOMER a system model is provide by entering the type of resources that are planed to be used, the resource availability, the technology options and the related costs for each of the components. Based on the input data, different system configurations, are simulated and a list of feasible system configurations sorted by net present cost is created.

When simulating a grid-connected microturbine and fuel cell supplying both heat and electricity, HOMER will operate the microturbine and fuel cell whenever doing so would save money compared to the alternative, which is to buy electricity from the grid and produce heat with a boiler [13].

After determining the feasible solutions of the hybrid energy system, which meet the requirements under the specified conditions, the costs for installation, replacement and operation of the system over the lifetime of the project are estimated. The system cost calculations account for costs such as: capital, replacement, operation and maintenance (O&M), fuel, and interest.

All presented graphs and figures in the paper are exported from the HOMER software after making personal modeling and simulation of the analyzed hybrid energy system.

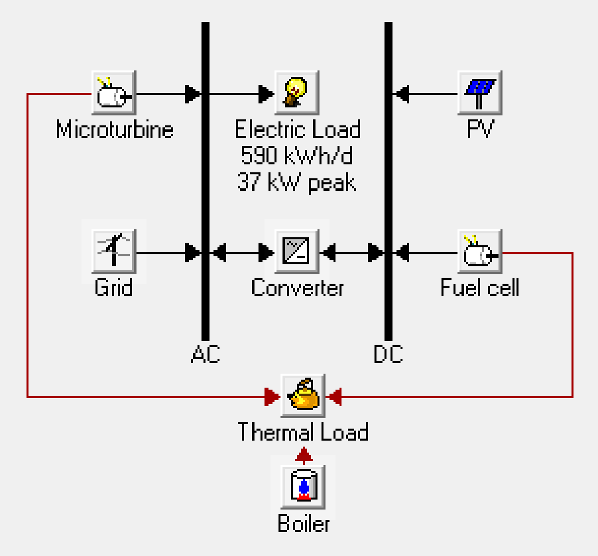


Fig. 1. Schematic representation of the hybrid energy system under consideration

3.1. Load data

Figure 2 and Figure 3 present the average daily electrical load profile and average daily thermal load profile for the industrial consumer that should supply from the analyzed hybrid energy system.

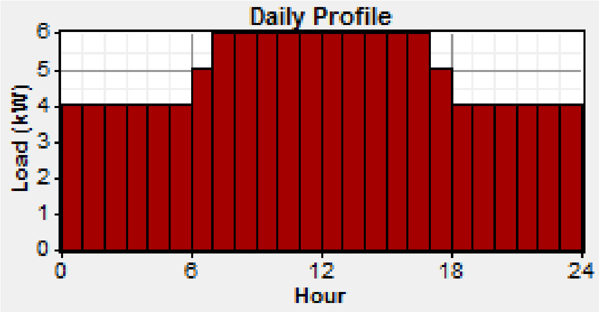


Fig.2. Average daily electrical load profile

Fig.3. Average daily thermal load profile

3.2. Characteristics of the components

PV system

Table 1 provides the data of photovoltaic system costs: capital costs (C_c), replacement costs (C_R), operation and maintenance costs ($C_{O\&M}$), [14]. The derating factor of the photovoltaics is chosen to be 90%. Photovoltaics are modeled with a fixed slope of placement. Lifetime of the photovoltaics is 25 years.

Table 1. Photovoltaic system costs

Size (kW)	C_c (\$)	C_R (\$)	$C_{O\&M}$ (\$/yr)
1	2710	2300	54

Fuel cell

The data of fuel cell costs are given in Table 2. Lifetime of the fuel cell is 40000 h. The fuel cell uses natural gas as a fuel. The fuel price is $0.15 \ \$/\mathrm{m}^3$.

Table 2. Fuel cell costs

Size (kW)	C_c (\$)	C_R (\$)	$C_{O\&M}$ (\$/h)
5	15000	12500	0.03

Microturbine

The costs for this component are given in Table 3, [15]. Lifetime is 55000 hours. The microturbine (generator is included in this component) uses natural gas as a fuel.

Table 3. Microturbine costs

Size (kW)	C_c (\$)	C_R (\$)	$C_{O\&M}$ (\$/h)
30	28500	25600	0.300

Inverter

The DC-AC converter is used which converts DC power from PV and FC converted into AC to be served as AC electrical load. The inverter efficiency is 90%. The costs for the converters used are given in Table 4. 5 kW size of inverter is considered. Lifetime is 15 years.

Table 4. Inverter costs

Size (kW)	C_c (\$)	C_R (\$)	$C_{O\&M}$ (\$/yr)
5	1250	1125	10

Grid

The grid supplies power to the system only when there is no enough electricity production from the components into the system to meet the electrical load demand and support the system. The following inputs are entered in this component: interconnection charge is 1556 $, purchase capacity is 10 kW, grid power price (here the tax for grid is also included) is 0.24 $/kWh.

3.3. Solar resource availability data

Solar energy as a resource is used for our location with Latitude 41.1396 and Longitude 22.4935. Data for solar radiation are taken from [16]. The average annual solar radiation for the selected location is $4.2 \ \mathrm{kWh/m^2/d}$. Figure 4 shows the profile of the average daily solar radiation in the individual months during a year.

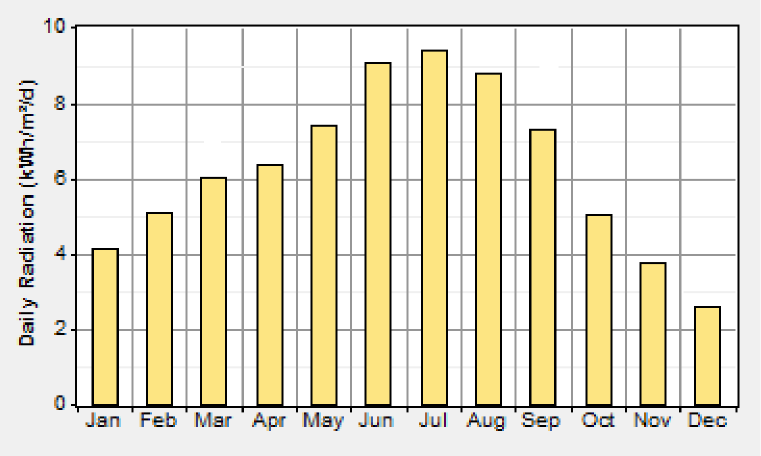


Fig.4. Average daily solar radiation profile in the individual months

4. RESULTS AND DISCUSSION

At first the basic generation scenario, for a grid-connected hybrid energy system consisting of 30 kW microturbine, 5 kW fuel cell, 5 kW photovoltaic system and 5 kW inverter is considered. In system control inputs the possibility for inclusion of multiple generators in the system and multiple generators to operate simultaneously is allowed.

The net present cost by cost type and by component is presented in Figure 5 and Figure 6 respectively. The net present cost for the whole hybrid system is 197,781 $. Also the salvage value is presented on the figure (2,699 $). Levelized cost of energy is $COE = 0.068[\$/\text{kWh}]$. The electricity production (kWh/yr) of MT/FC/PV and grid purchases are presented in Table 5. Monthly average thermal production is given in Figure 7. The renewable fraction in this case is 0.0298.

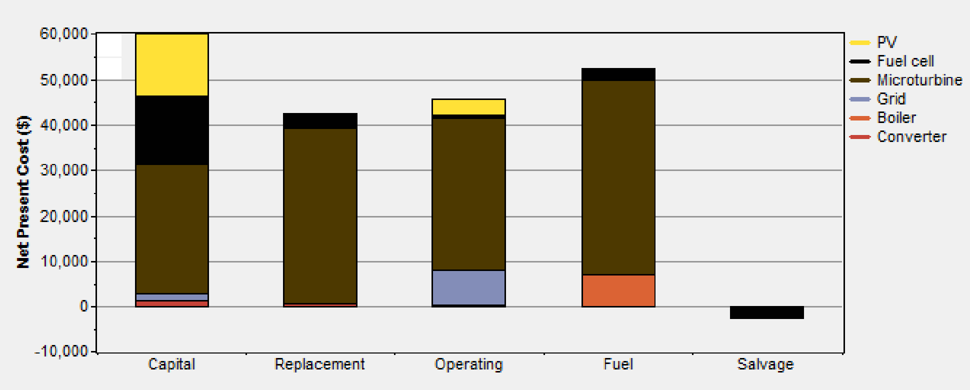


Fig. 5. Net present cost by cost type

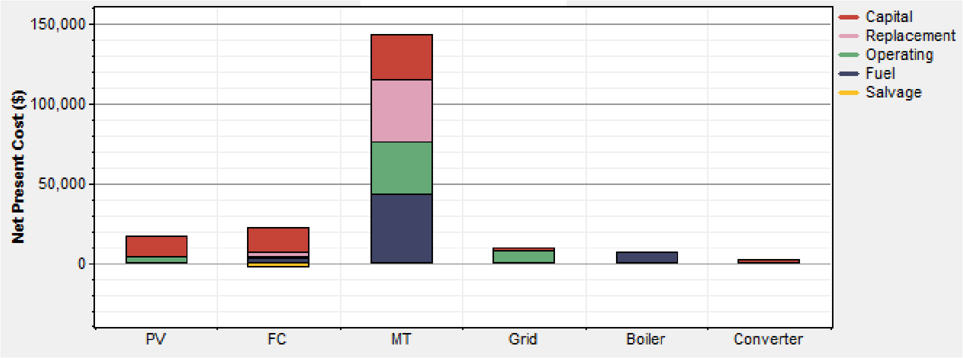
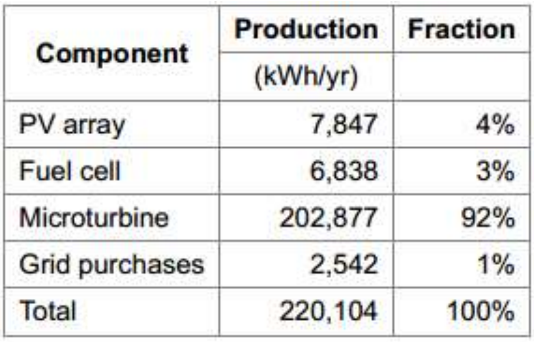


Fig. 6. Net present cost by component

Table 5. Electricity production of MT/FC/PV system



Component	Production (kWh/yr)	Fraction
PV array	7,847	4%
Fuel cell	6,838	3%
Microturbine	202,877	92%
Grid purchases	2,542	1%
Total	220,104	100%

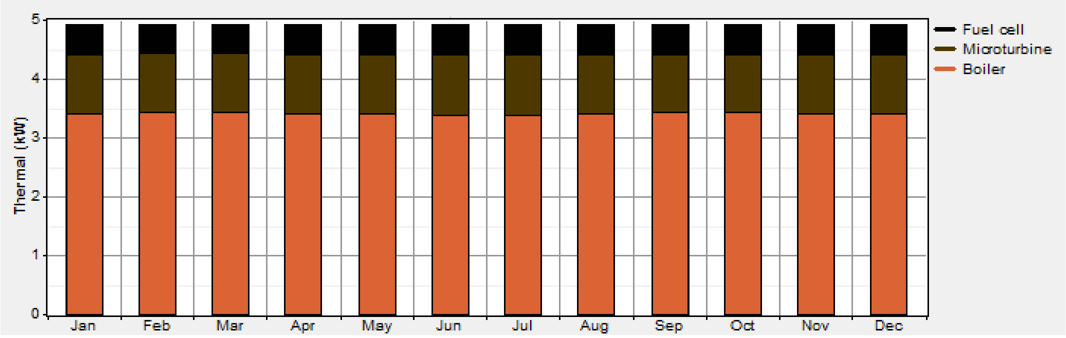
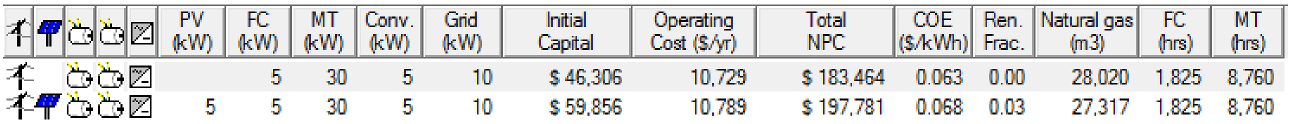


Fig. 7. Monthly average thermal production

If we analyze systems with the presence and absence of PV, MT and FC and allowed multiple generators to operate simultaneously, then 2 feasible solutions of the system are generated (MT/FC and MT/FC/PV) sorted by total net present cost. Some of the results for these two systems are given in Figure 8. The simulation results show that the optimal system is the system with microturbine and fuel cell (Total NPC is 183,464 $). Levelized Cost of Energy is $COE = 0.063[\$/\mathrm{kWh}]$. Figure 9 presents the discounted cash flow over the project lifetime (costs and salvage value) for the optimal system. The pollutant emissions by operating of the MT/FC/PV and MT/FC hybrid energy systems are given in Table 6. If we compare the results it is clear that from the MT/FC system all pollutant emissions are higher, because of the absence of PV and higher consumption of natural gas.



	PV (kW)	FC (kW)	MT (kW)	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Natural gas (m3)	FC (hrs)	MT (hrs)
		5	30	5	10	$ 46,306	10,729	$ 183,464	0.063	0.00	28,020	1,825	8,760
	5	5	30	5	10	$ 59,856	10,789	$ 197,781	0.068	0.03	27,317	1,825	8,760

Fig. 8. Feasible solutions sorted by total net present cost for the second analyzed case

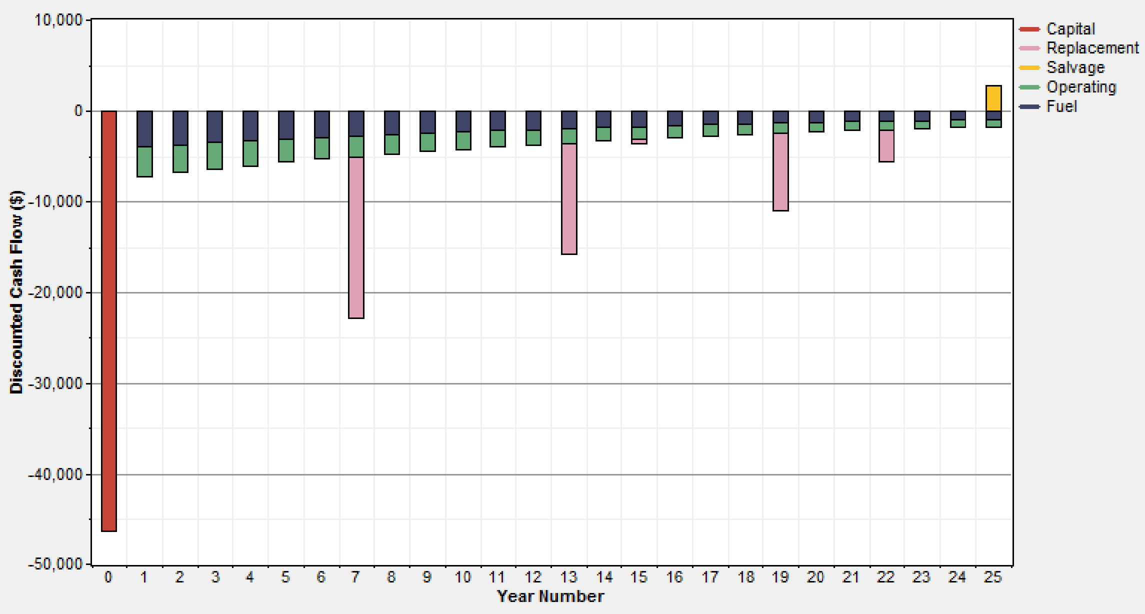
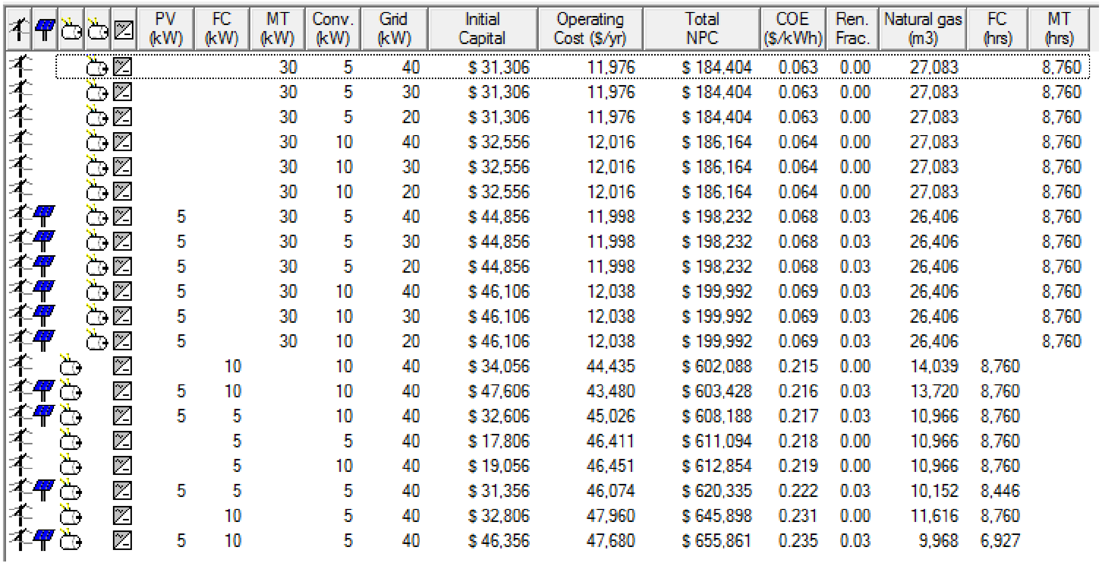


Fig. 9. Discounted cash flow over the project lifetime for the optimal system (MT/FC)

Table 6. Pollutant emissions

Pollutant	**Emissions (kg/yr)**	
	MT/FC/PV	**MT/FC**
Carbon dioxide	52,732	54,086
Carbon monoxide	154	159
Unburned hydrocarbons	17.1	17.6
Particulate matter	11.6	12
Sulfur dioxide	140	143
Nitrogen oxides	1,378	1,421

Another case that is analyzed is if in the system control inputs, the possibility for inclusion of multiple generators in the system and multiple generators to operate simultaneously **is not allowed**, so the system with MT and FC will not be listed in this case. Also, the following inputs for the components are added: fuel cell size: 0 kW, 5 kW and 10 kW, inverter size: 5 kW and 10 kW, and grid purchase capacity: 10 kW, 20 kW, 30 kW, 40 kW. The generated list of feasible solutions of the system, in this case, with some of the result are presented in Figure 10. While, Figure 11 presents categorized feasible solutions sorted by total net present cost for this analyzed case.



PV (kW)	FC (kW)	MT (kW)	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Natural gas (m3)	FC (hrs)	MT (hrs)
		30	5	40	$ 31,306	11,976	$ 184,404	0.063	0.00	27,083		8,760
		30	5	30	$ 31,306	11,976	$ 184,404	0.063	0.00	27,083		8,760
		30	5	20	$ 31,306	11,976	$ 184,404	0.063	0.00	27,083		8,760
		30	10	40	$ 32,556	12,016	$ 186,164	0.064	0.00	27,083		8,760
		30	10	30	$ 32,556	12,016	$ 186,164	0.064	0.00	27,083		8,760
		30	10	20	$ 32,556	12,016	$ 186,164	0.064	0.00	27,083		8,760
5		30	5	40	$ 44,856	11,998	$ 198,232	0.068	0.03	26,406		8,760
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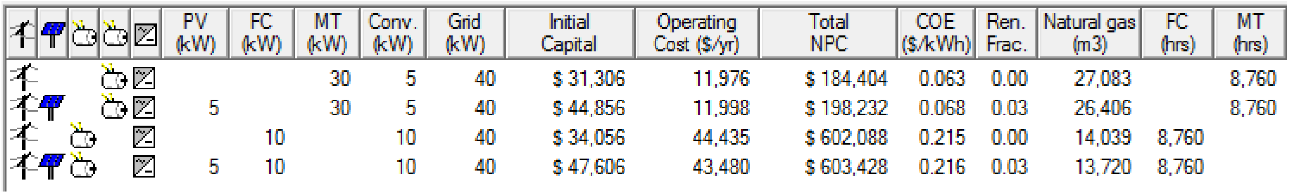
5		30	5	20	$ 44,856	11,998	$ 198,232	0.068	0.03	26,406		8,760
5		30	10	40	$ 46,106	12,038	$ 199,992	0.069	0.03	26,406		8,760
5		30	10	30	$ 46,106	12,038	$ 199,992	0.069	0.03	26,406		8,760
5		30	10	20	$ 46,106	12,038	$ 199,992	0.069	0.03	26,406		8,760
	10		10	40	$ 34,056	44,435	$ 602,088	0.215	0.00	14,039	8,760	
5	10		10	40	$ 47,606	43,480	$ 603,428	0.216	0.03	13,720	8,760	
5	5		10	40	$ 32,606	45,026	$ 608,188	0.217	0.03	10,966	8,760	
	5		5	40	$ 17,806	46,411	$ 611,094	0.218	0.00	10,966	8,760	
	5		10	40	$ 19,056	46,451	$ 612,854	0.219	0.00	10,966	8,760	
5	5		5	40	$ 31,356	46,074	$ 620,335	0.222	0.03	10,152	8,446	
	10		5	40	$ 32,806	47,960	$ 645,898	0.231	0.00	11,616	8,760	
5	10		5	40	$ 46,356	47,680	$ 655,861	0.235	0.03	9,968	6,927	

Fig. 10. Overall feasible solutions sorted by total net present cost for the third analyzed case



PV (kW)	FC (kW)	MT (kW)	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Natural gas (m3)	FC (hrs)	MT (hrs)
		30	5	40	$ 31,306	11,976	$ 184,404	0.063	0.00	27,083		8,760
5		30	5	40	$ 44,856	11,998	$ 198,232	0.068	0.03	26,406		8,760
	10		10	40	$ 34,056	44,435	$ 602,088	0.215	0.00	14,039	8,760	
5	10		10	40	$ 47,606	43,480	$ 603,428	0.216	0.03	13,720	8,760	

Fig. 11. Categorized feasible solutions sorted by total net present cost for the third analyzed case

5. CONCLUSION

A grid-connected combined heat and power system consisting of microturbine, fuel cell, photovoltaic system and inverter has been investigated. The objective of this study was to determine the optimal configuration of the system, which should meet the electrical and thermal load, respecting the total net present cost. The system has been modelled in HOMER software and this tool was used to perform simulation, calculation and optimization. Emissions of pollutants by operating of the MT/FC/PV and MT/FC hybrid energy systems have been analyzed too.

Technical and economic data of the system's components that have been modeled, as well as solar resource availability, fuel price, data for the electrical and thermal load are used as inputs into the software tool.

After determining the feasible solutions of the hybrid energy system, which meet the requirements under the specified conditions, the costs for installation, replacement, operation and maintenance, as well as salvage value of the system over the lifetime of the project have been estimated. Also, electricity and thermal energy production by each component, grid purchases, levelized cost of energy, renewable fraction, natural gas consumption, emissions of pollutants are some of the output results that have been calculated and presented in the paper in section 4.

The study found the following key points:

- For grid purchase capacity of 10 kW the cost effective system is with microturbine (30 kW) and fuel cell (5 kW), without photovoltaic system. The difference of net present costs between MT/FC/PV system and MT/FC system is 14,317$. But, on the other hand by operating of the MT/FC hybrid energy system the pollutant emissions are higher than in case of MT/FC/PV system.
- If the microturbine and fuel cell are not allowed to operate simultaneously in the system then the grid purchase capacity should be greater than 10 kW in order to have feasible solution in this case. Under considered inputs in this case:
  - The cost effective system is with 30 kW microturbine connected on grid with 40 kW purchase capacity.
  - From the categorized feasible solutions next systems sorted by total net present cost is with 5 kW PV and 30 kW MT connected on grid with 40 kW purchase capacity, system with 10 kW FC connected on grid with 40 kW purchase capacity and the last one is the system with 5 kW PV and 10 kW FC.
  - In the system with integrated fuel cell there is feasible solution only if the grid purchase capacity is 40 kW.

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