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An analysis of hybrid power generation systems for a residential load

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Abstract This paper presents the results of an energetic and economical analysis of a hybrid power generation system (HPGS) which utilises photovoltaic modules, wind turbines, fuel cells and an electrolyzer with hydrogen tank working as the energy storage. The analysis was carried out for three different residential loads, local solar radiation and local wind speed, based on the real measurement values. The analysis shows the optimal solution and the limits of the investment costs required for the system construction. The presented results confirm the effectiveness of the proposed approach, which could be assumed as a very useful tool in the design and analysis of a hybrid power generation system.

1 Introduction

The global challenge of providing reliable, clean and cost-effective energy remains one of the major challenges which the world is facing with this century [1]. The renewable energy sources are considered as the most important and most effective solution for the future. The wind energy and the solar energy are considered as the most effective among the various rentable energy resources, they have made a rapid and substantial breakthrough in last year's [2].

Solar energy is an inexhaustible source used depending on various techniques such as solar systems [3]. The power generated by the photovoltaic systems is a proven method with a large number of applications throughout the world [4]. The photovoltaic system can be integrated with the grid connection (grid-on) or can be autonomous systems (grid-off). Usually photovoltaic system consists of the photovoltaic modules, storage batteries, inverters and power control components sometimes with mechanical or electronic tracking systems. From the local point of view the photovoltaic systems are zero greenhouse gases emissive which make energy generation environmentally friendly. In addition to the flexible process ability to expanded for meeting the growing energy needs furthermore cost effective and minimal maintenance requirements.

Wind energy is an important energy source, environmentally and economically competitive and expected to have a significant role to meet the global challenges of clean energy and sustainable development under climate change [5-7]. After the first oil crisis was

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introduced wind energy is considered as a medium that uses local resources and promotes energy independence, security, and decentralization of power system [8].

1.1 Hybrid power system configuration and optimization

The hybrid power generation system (HPGS) optimal (or possible) configuration depends on three main factors: energy resource (conventional and/or renewable), demanded load, and the cost (operating expenditure and capital expenditure) [8]. The main problem which face power generation using a hybrid power system is the variation in renewable resources (wind speed and solar radiation) and the variation in load demand. Therefore, the majority concern in the design of the hybrid power system that uses renewable energy sources is the best choice of components for the system that can meet the load demand and economically pregnancy. Based on the components operating cost, fuel, labor and transportation, maintenance and highly desirable to assess the most cost-effective scaling of all components to meet peak loads.

The system size optimization of hybrid power system has to reduce the net present costs while meeting demand as reliable and cost effective. In this work the computer simulation model has been developed to optimize hybrid power generation system which utilises photovoltaic modules (PV), wind turbines (WT), PEM fuel cells (FC), electrolyzer (EL) and hydrogen tank (HT) as the energy storage. The main purpose of this project is to study the possibility of interbreeding renewable energy sources through the design and optimization of the hybrid PV/WT/FC system used based on the optimal computer design.

In order to utilize in the economical and efficient way renewable energy resources, it is important to optimise the size of system components. The optimal system components sizes can help to ensure minimum investment cost with the fully use of the system components. In such cases the hybrid system can operate in the optimal conditions in terms of the investment as well as in terms of the energy system reliability requirements. Solar and wind energy systems are renewable energy systems resources, with and without the grid connection widely used among the most developed ones. The sizing tool determines the optimum size of the system components. In hybrid energy power systems around 35% of the total energy is lost due to the non-optimum size of the system [9]. The optimal configurations can be found by using the computer simulation. The Matlab simulation has been used in order to obtain the optimum configuration and the sizes of the system components.

In the last decades large number of the research projects, technologies and configurations which concentrate on the optimal design of the hybrid power system components have been done. Juhari et al. [10] optimized energy systems in the context of the minimizing cost of energy and excess energy. Kellog et al. [11], optimized the unit size of the hybrid photovoltaic/wind power system. Kamaruzzaman et al. [12] optimize the operational strategy of the components cost. The calculation using Net Present Cost (NPC) as the key function to minimise in the case of hybrid energy systems design was done by Lambert et al. [13]. Kamel et al. [14] used HOMER software in order to find the optimum components size at lowest cost for the hybrid power system in stand-alone applications. Fahmy et al [15] design an optimal economic renewable hybrid power system depending on wind & solar radiation and showed these two sources of energy can have a high effect on reducing COE more than other renewable energy sources. Khare et al [16] presented the methodology for components size calculation as well as for stand-alone PV/diesel/battery hybrid system optimization. Shivrath et al. [17] shows methodology for optimally designed the solar and wind hybrid system for a remote drip irrigation system. Rashidi et al.[18] was focused on the optimal design of a standalone solar-hydrogen system.

1.2 Study Area

Poznań is a city located on the Warta River in western Poland with renewable energy resources such as the wind and solar radiation that can be exploited for alternative energy solutions. Poznań is situated in latitude 52'4064° N and longitude 16'9252° E with abundant wind speed most the year round. According to Poznań weather stations this area is endowed with an annual wind speed average 6 m/s and has an annual average daily solar radiation of about 2.81 kW/m^2/day.

2 Energy analysis of hybrid power generation system

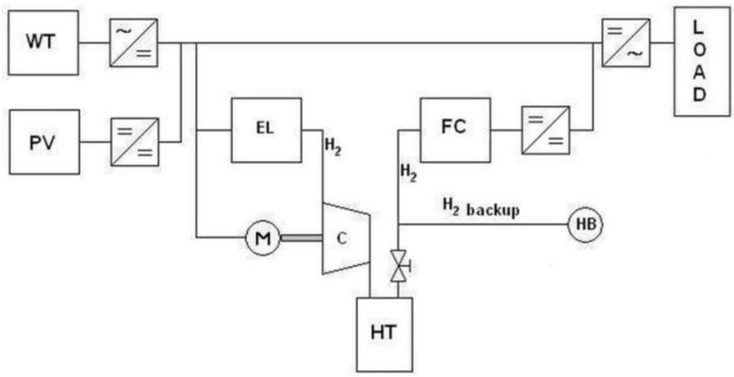

Fig. 1. Flowchart-hybrid power generation system.

Hybrid power generation system flowsheet analysed in this paper is shown in Fig. 1.

Temporary power shortages associated with stochastic nature of the generation of energy by renewable sources is compensated by fuel cell operation. This mode of operation is enabled by operating characteristics of fuel cells, which are perfectly suited for varying loads and show high efficiency in a wide power range. A very valuable feature of fuel cells is their high efficiency at low load at 45-55 % for PEM fuel cells. Primary, hydrogen is supplied from the hydrogen tank HT. In the case of running out hydrogen in the tank, the fuel cell is powered by the hydrogen backup HB. The use of additional hydrogen in the backup purposes may be subjected to small emissions of pollution associated with its production, depending on the used technology (steam reforming of hydrocarbons, coal gasification and biomass gasification).

The balance of the power in the system, depends on the ratio of power generated by renewable energy sources RES to the demand of the energy load. For the cases where the demand is lower than the energy power balance equation takes the following form:

$$P_{load} = P_{PV} + P_{WT} - P_{EL} - P_{comp} \tag{1}$$

where: P_{load} [kW] – power consumed by the recipient, P_{PV} [kW] – power generated by photovoltaic installation, P_{WT} [kW] – power generated by wind power plants, P_{EL} [kW] – power consumed by the electrolyzer, P_{comp} – power used for compression of hydrogen.

If the demand exceeds the power generated by the sources, the energy power balance equation takes the form:

$$P_{load} = P_{PV} + P_{WT} + P_{FC} \tag{2}$$

where: P_{FC} [kW] – power generated by the fuel cell.

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Energy analysis was conducted on the basis of the balance equations (eq.1 and eq.2.) produced and received from hybrid power generation system. The analysis was carried out for three different residential loads, local solar radiation and local wind speed, all based on the real measurement values. The Fig. 2 and 3 shows the annual timetables of solar energy distribution and wind speed for which distribution technical-economic analysis be adopted.

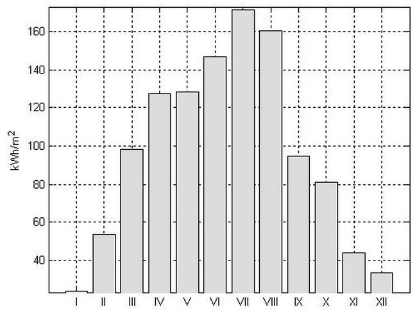

Fig. 2. The annual distribution of solar energy.

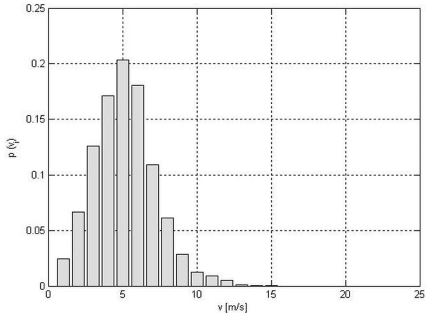

Fig. 3. The annual distribution of wind speeds.

The Fig.4, 5 and 6 show the weekly energy profiles of recipient 1,2 and 3. Profile 1 for is a two-person apartment where a gas oven and gas cooker are installed. The second profile is a family of four where all devices are powered by electrical energy (no gas installation). The third profile is a student apartment. In this case, the students occupy the apartment for four days a week. The rest of the time they spend in their hometowns.

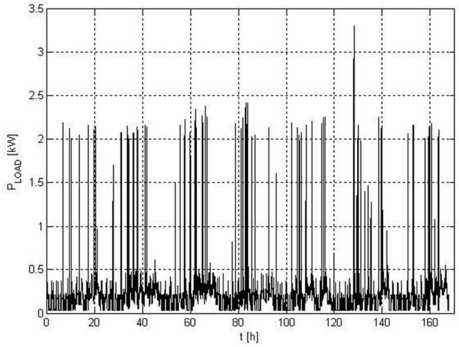

Fig. 5. The energy profile of the recipient 2.

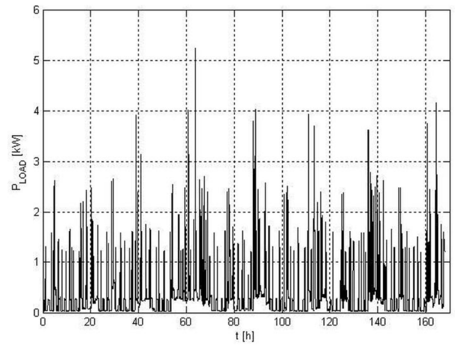

Fig. 4. The energy profile of the recipient 1.

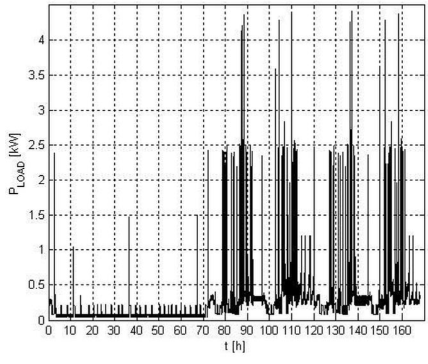

Fig. 6. The energy profile of the recipient 3.

In order to compare the profiles, annual electricity consumption by individual customers the following values has been designated: the instantaneous value of the maximum power consumption by the given receiver P_{max}, average power value P_{av_load} and an annual energy consumption A (see Table 1).

Table 1. Comparison of recipients.

	Recipient 1	Recipient 2	Recipient 3
A [MWh/a]	1.62	3.04	2.35
P_{av_load} [kW]	0.19	0.35	0.27
P_{max} [kW]	3.37	5.22	4.4

With a view to the selection of the composition of the generating units to meet the needs of the customer, we used the following equations [19]:

$$\Delta P = P_{av\_gen} - P_{av\_load} \rightarrow \min \tag{3}$$

$$P_{av\_gen} = n_{cf\_PV} \cdot P_{PV} + n_{cf\_WT} \cdot P_{WT} \tag{4}$$

where: P_{av_gen} – power generated by renewable sources, P_{av_load} – average input power by the recipient, n_{cf} – capacity factor of each renewable energy sources.

The value under the average for the period T_a is designated with the dependencies:

$$P_{av\_PV} = \frac{A_{PV}}{T_a} \tag{5}$$

$$A_{PV} = W_k \cdot W_w \cdot \int_0^T P_{PV}\, dt \tag{6}$$

where: A_{PV} – energy produced by photovoltaic system at time t, W_k – correction factor that takes into account the angle of installation referral to the south and the angle of deviation of the modules from the level, W_w - coefficient of performance.

For the determination of the amount of electricity produced by photovoltaic modules there were used the characteristics of the P_{PV} = f (E) developed on the basis of external characteristics family U = f (I) (see Fig. 7). Photovoltaic modules system is equipped with an MPPT maximum power point tracking ($P_{PV} = P_{MMP}$) [20].

In order to determine the average power produced by wind turbines P_{av_WT} operational characteristics was implemented P = f(v) and the distribution of wind speeds was presented in the form of a continuous function f(v) using the Weibull distribution (see Fig. 8):

$$f(v) = \frac{k}{\lambda}\left(\frac{v}{\lambda}\right)^{k-1} e^{-(v/\lambda)^k} \tag{7}$$

where: v - wind speed [m/s], k - shape parameter (k > 0), λ - the scale parameter (λ > 1)

$$P_{av\_WT} = \int_0^\infty P(v) f(v)\, dv \tag{8}$$

Energy storage has been selected basing on the following assumptions:

- fuel cell is able to meet the instantaneous maximum demand:

$$P_{FC} = P_{\max\_load} \tag{9}$$

- electrolyzer is able to accept temporary power generated by photovoltaic system and wind sources:

$$P_{EL} = m \cdot (P_{max\_WT} + P_{max\_PV}) - P_{min\_load} \tag{10}$$

where: P_{EL} – rated electrolyzer power, P_{max_WT} – the maximum instantaneous wind turbines, P_{max_PV} – instantaneous maximum power photovoltaic installation, P_{min_load} – minimum instantaneous customer demand, m – coefficient of simultaneity of maximum power generation by the photovoltaic system and the wind turbine.

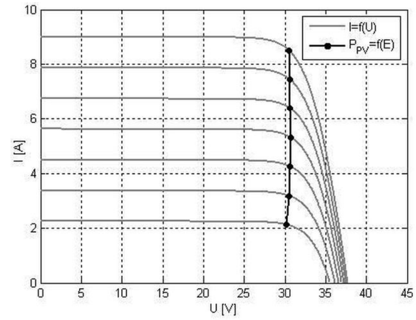

Fig. 7. External characteristics of PV modules family.

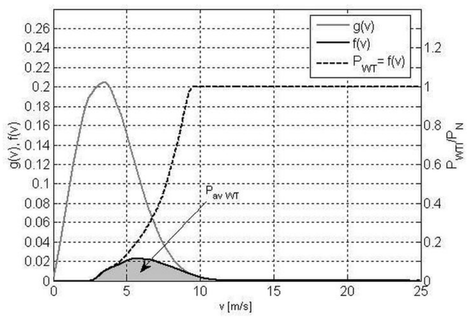

Fig. 8. Determination of annual average wind power capacity.

To determine the amount of the hydrogen produced by the electrolyzer and the quantities of hydrogen consumed by fuel cell, the characteristics P= f(V_{H2}) (see Fig. 9) developed on the basis of external characteristics of the fuel cell and electrolyzer U = f(I) (see Fig. 10) was used.

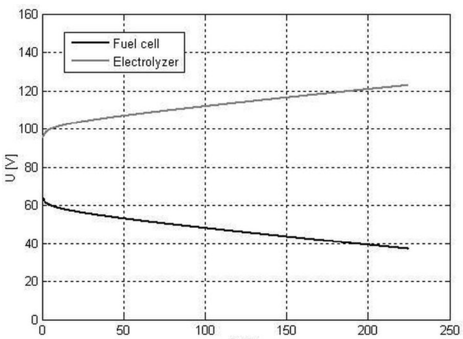

Fig. 9. The characteristics U = f (I) of fuel cells and the electrolyzer.

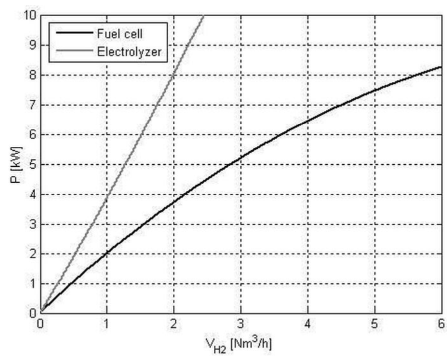

Fig. 10. The characteristics P = f (V_{H2}) of fuel cells and the electrolyzer.

Basing on the equations 1 - 10 and the authorial code written in MATLAB it has been chosen a set of devices of a hybrid system and the annual demand for additional hydrogen for each customer has been specified in order to ensure uninterrupted power supply. The results for the hybrid system are shown in Table 2.

In order to determine the optimal composition of the generating units of the hybrid power generation system for each of the profiles, two additional variants were considered, except for the basic variant (PV and WT):

PV variant – the source of renewable energy as only photovoltaic installations, hybrid system is not equipped with wind power plants.

WT variant – the source of renewable energy are the only wind power plants, hybrid system is not equipped with photovoltaic installations.

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Table 2. Comparison of recipients

	Basic Variant PV + WT			Variant PV			Variant WT		
Recipient	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
RES nominal power [W]	1050	1850	1350	1500	2750	2250	600	1200	900
Photovoltaic modules [W_p]	3x250	5x250	3x250	6x250	11x250	9x250	-	-	-
Wind turbines [W]	1x300	2x300	2x300	-	-	-	2x300	4x300	3x300
Fuel cell [kW]	3	5	4.2	3	5	4.2	3	5	4.2
Elecktrolyzer [kW]	1	1.5	1.2	1.5	2.5	2	1	1.5	1
H_2 backup [Nm^3]	**459.4**	**812.6**	**464.9**	**706.6**	**1130.3**	**774.64**	**443.73**	**606.2**	**476.73**

By analyzing the results of the calculations, it can be concluded that the differences between the demand for hydrogen for the variant "WT" and "PV + WT" are marginal. On the other hand, in the case of the variant "PV", resignation from wind turbines must be compensated by more frequent work of the fuel cell and much larger hydrogen consumption from back-up HB. This is related to the fact that the photovoltaic installation works only during daylight and its power strongly depends on the solar power radiation. During the cloudy days or at night, the recipient will always be powered by fuel cells. This relationship applies to all the profiles of the concerned recipients.

The smallest value of nominal power P_N was obtained for the variant excluding PV system. It should be noted that the analysis assumes the wind profile obtained on the basis of annual measurements.

Conducted energy analysis is the basis for economic analysis, which gives a full comparison of the variants considered.

3 Hybrid power system components with an economical constraints and analysis

Three different configurations are considered in this analysis. The each configuration has different size and components illustrated in Table. 2. The main components are wind turbine (WT), Photovoltaic modules (PV), Converter, Fuel cells (FC), Electrolyzer (EL) and Hydrogen tank (HT), The cost, number of units to be used, operating hours, etc. need to be specified in MATLAB for all equipment's. The description of all these components is given in the following sections. In the present simulation, the main component include two major renewable energy which photovoltaic panel & wind turbine with a fuel cell as a storage unit. The photovoltaic panel & fuel cell involved inverter for AC/DC and an electrolyzer used with hydrogen tank to feed the fuel cell. The system schematic diagram is shown in Fig. 1.

3.1 Wind turbine unit

The wind is the source of energy in wind turbine unit. In general the production depends on the wind variation, and in this work annually average (6 m/s) is considered as in the selected site. The wind turbine unit size considered (0.3 kW AC), the installation and replacement costs of this size taken as ($1000) with operation & maintenance cost ($100/yr) for (20 years) lifetime.

3.2 Photovoltaic array and power converter model

The photovoltaic array is the second energy producer unit, affected by solar radiation variation. The installation and replacement costs of (1 kW) solar energy systems are taken as ($1000) with operation & maintenance cost ($300/yr) and the lifetime was taken (20 years) without sun tracking system.

An electronics power converter is needed to maintain energy flow between the (DC) and (AC) components. The installation and replacement costs of (1 kW) are taken as ($500) with operation & maintenance cost ($200/yr) and a lifetime of a unit are considered (15 years) with an efficiency 85 %.

3.3 Fuel cell, electrolyzer and hydrogen tank unit

A fuel cell is the energy storage unit in this system. A commercial type model with size (3 kW) for all configurations was considered in this simulation. The estimated lifetime is (30000 hr) and the installation with replacement costs are taken ($500/kW) while the maintenance cost is expected at ($ 0.1/hr).

The electrolyzer is the device that produces hydrogen by using electrical load and at the same time consider one of two main loads on the system. The installation and replacement costs are taken is ($500/kW) with operation & maintenance cost ($500/yr) and the lifetime (20 years).

The hydrogen tank is a part of this system that is the storage of hydrogen produced from electrolyzer which used to feed the fuel cell. The installation with replacement costs is taken ($500/kg) with operation & maintenance cost ($300/yr) and the lifetime (25 years).

4 Results

The project lifetime considered (20 years) with an annual discount rate of 1% for all configurations. After simulation and optimization system components for each configuration found the optimal contribution of each component to each combination, the annual electricity production for each configuration is illustrated in Table 3.

Table 3. Electricity production of hybrid system components

Configuration 1			**Configuration 2**		**Configuration 3**	
Production component	**kWh/year**	**%**	**kWh/year**	**%**	**kWh/year**	**%**
PV array	827	5	1.756	49	0	0
WT	12.362	81	0	0	24.724	94
FC	2.156	14	1.812	51	1.676	6
Total	15.345	100	3.567	100	26.399	100

Table 4 and Figure 11 show the cash flow summary for the optimal system for each configuration for all components, capital cost, replacement cost, operation and maintenance cost and salvage value. For the configuration 1, the total capital cost is considered to be ($6500) and the configuration 2, considered ($6500) and configurations 3, considered ($6000) for whole project lifetime.

The cost of electricity (COE $/kWh) and total net present cost (NPC $) for each configuration of the hybrid power system is shown in Figure 12 where the configuration 1 (COE is $0.287 and NPC $7962), configuration 2 (COF is $0.301 and NPC $8359) and configuration 3 (COE is $0.243 and NPC $6739) are summarized.

Table 4. Overall cost for each component of all combinations for hybrid power system

	Configuration 1			**Configuration 2**			**Configuration 3**		
	Capital ($)	Replace ($)	O&M ($)	Capital ($)	Replace ($)	O&M ($)	Capital ($)	Replace ($)	O& M ($)
PV	750	0	41	1.500	0	81	0	0	0
WT	1.000	0	180	0	0	0	2.000	0	0
FC	1.500	0	776	1.500	0	74	1.500	0	604
Conv	1.250	1.077	90	1.250	1.077	90	1.000	861	72
EL	1.000	0	90	1.500	0	135	1.000	0	90
HT	1.000	0	108	750	0	81	500	0	54
Total	**6.500**	**1.077**	**1.286**	**6.500**	**1.077**	**462**	**6.000**	**861**	**821**

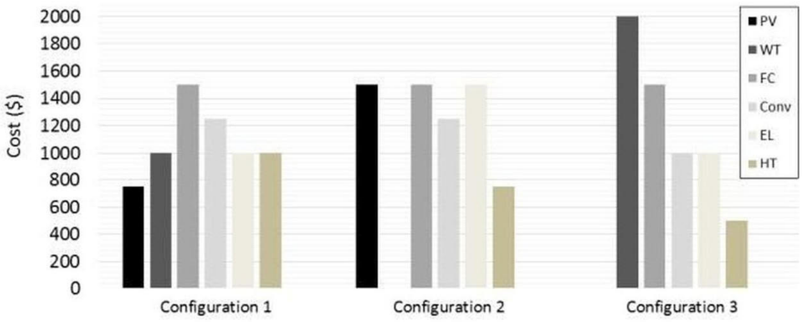

Fig. 11. Cash flow summary for components cost of all combinations for hybrid power system.

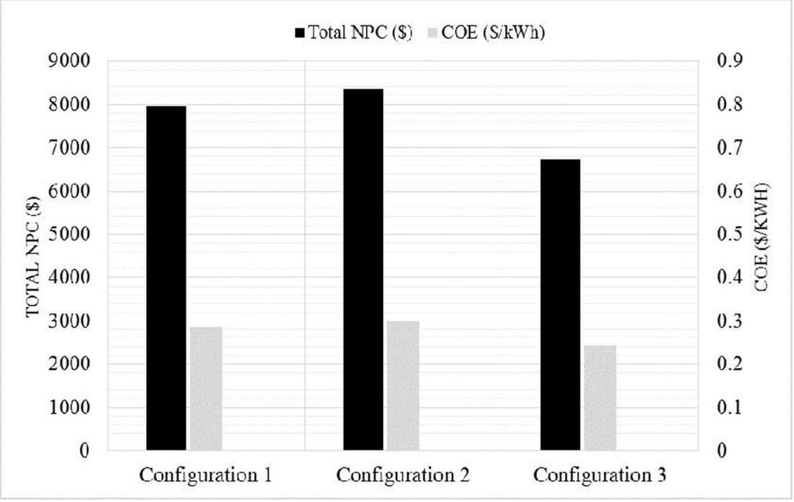

Fig. 12. Cost of electricity and total net percent cost for hybrid power system configurations.

5 Conclusions

The electrification using hybrid power systems are worldwide very promising in the recent years. Solar and wind power are considered as the renewable energy resources due to their high reliability and safety as well they are zero emissive. This study presents a complete analytical design of three configurations of the hybrid power systems with optimizing units for different loads presented in figures 4, 5, 6. The simulation and optimization results for each configuration has been prepared and the electricity demand can be met with a hybrid system comprising.

Resulting, the systems can be profitable with a reasonable investment for production renewable energy. It utilizes all renewable energy, component PV, WT and storage unit FC as showed in Table 3. However, the reliability of the system is ensured due to used high-reliability storage unit. The cost of energy generated from the above configurations has been found to be \$0.287, \$0.301, and \$0.243 for the configuration 1, 2 and 3 respectively and the price can be very beneficial and suitable for long-term investments particularly with partial governmental support. Also the nature of the hybrid power system is environmentally-friendly that can be depicted from the annual emissions.

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