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Economic analysis of PV/diesel hybrid system with flywheel energy storage

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ABSTRACT

This paper analyzes a hybrid energy system performance with photovoltaic (PV) and diesel systems as the energy sources. The hybrid energy system is equipped with flywheel to store excess energy from the PV. HOMER software was employed to study the economic and environmental benefits of the system with flywheels energy storage for Makkah, Saudi Arabia. The analysis focused on the impact of utilizing flywheel on power generation, energy cost, and net present cost for certain configurations of hybrid system. Analyses on fuel consumption and carbon emission reductions for the system configurations were also presented in this paper.

1. Introduction

Since the past few decades, electricity demand in the world has been increasing drastically due to human population growth. As a matter of fact, most of the electricity demand is supplied by electricity generated from fossil fuels such as natural gas, fuel oil and coal. However, the use of fossil fuels in electricity generation causes carbon dioxide (CO_2) emissions which affect the environment negatively. This problem has to be encountered by searching and developing local alternative energy resources to substitute the energy from fossil fuels. There have been numerous instances of alternative energy resources being intensively implemented, i.e. solar, wind, biomass, and hydroelectric energy.

In recent years, many efforts have been made to increase the implementation of renewable sources of energy through researches and application, not only in the developed countries but also in the developing countries. For instance, Connoly et al. have conducted research on the initial step to develop an energy system based on 100% renewable sources in Ireland. It has been concluded that serious efforts should be made in order to have gradual transition to renewable energy in the future [1]. Apart from significant efforts to diversify energy sources, a future energy mix has been proposed to replace supply energy from combustion of fossil fuels and support sustainable energy development in the country [2,3].

It has been demonstrated that compared to diesel energy supply, renewable energy supply was techno-economically feasible for the small and medium scale of tourist operations, and for the grid connected hotel in Australia [4,5]. Himri et al. have reviewed the implementation of renewable energy and its future objective in Algeria [6], while the availability of renewable energy resources in Brunei has been researched by Malik [7]. In developing countries, hybrid renewable energy systems especially solar PV and diesel generators have been seen as a promising energy supply for now and the future. In specific studies, Phuangpornpitak and Kumar have discussed diesel/PV hybrid system performances in Thailand [8,9].

Some feasibility studies on utilizing PV/diesel system in supplying energy for local load needs have been done around the globe [10–14]. Feasibility studies have also been carried out to assess the potential of the renewable energy sources in Saudi Arabia [15–17].

The usual gap that appears between supply and demand of electricity calls for the use of electrical energy storage (EES) system. Batteries are the most common technology used for EES systems in renewable energy power systems. The purpose of EES systems is to alleviate the mismatch between the power demands and electricity generation. Other than batteries, there are various technologies available for EES system, but no single EES system appropriates the ideal EES requirements, i.e., high density, high efficiency, low costs, long lifetime, and environmentally friendly [18]. For that reason, it

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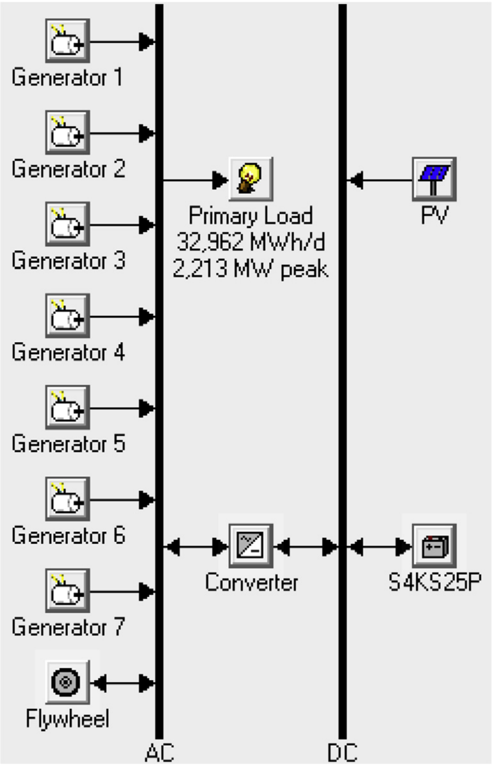

Fig. 1. Designed configuration of PV/diesel hybrid system with flywheel energy storage using HOMER software.

is necessary to combine more than one EES technology in a power system [19,20].

Nowadays, the lead-acid, nickel, and lithium-based batteries have been used extensively [21]. According to the report, typical efficiency in a lead-acid battery is 85–90%, in a nickel-based battery it is 65–83%, and a lithium-based battery could have up to 95% round-trip efficiency. The lead acid-batteries have been widely used in renewable energy power systems due to their low cost and relatively high energy efficiency. However, having low energy density, large size and weight, short cycle life, and limited discharge capability are the main drawback of lead-acid batteries. A lead-acid battery has higher energy density and long life cycle than a nickel-based battery. However, nickel-based batteries have a less energy efficiency when compared to the lead-acid batteries. Moreover, the nickel-based batteries are more expensive in terms of cost than lead-acid batteries. As compared to both lead-acid and nickel-based batteries, a lithium-based battery is superior in energy efficiency and energy density. The lithium-based batteries are becoming a main choice for stationary EES, often in conjunction with flow batteries.

Several stand-alone PV-lead-acid battery systems are examined in Ref. [22], where in all scenarios the impact of the battery component analyzed exceeds 27% of the system life cycle energy requirements. Incorporation of storage elements on the stand-alone PV systems renders them more productive than when they do not have energy storage elements. In all these cases, the proper component sizing has to be done for example by using a graphical construction technique to follow the optimum combination of PV array and battery for a hybrid system [23]. The use of battery as a backup mechanism has demonstrated an ability to increase the renewable energy penetration in grid-connected PV systems [24]. Moreover, a robust backup system can guarantee the improvement of the energy supply reliability especially in remote rural areas where grid extension is not economical [25].

Flywheel is another EES system that is being used today. The use of flywheel avails another backup alternative to improve the energy supply reliability and possibly reduce the use of diesel generation. Compared with batteries, flywheels usually have high initial cost. However, the flywheels have a much higher power density than the batteries. The flywheel is competitive with battery in applications of power storage. For longer storage time, it is suitable for lower loss and reduced cost systems. The flywheel has some advantages including high energy density, long life cycle, environmentally friendly, less maintenance required, high depth of discharge (DOD), large number of charge and discharge cycles, high round-trip efficiency, and the rapid charge and discharge rates. The flywheels efficiency is very high and typically ranges from 91 to 96% [26,27]. However, by way of economic standing and efficiency it is less than batteries.

For electric power systems, flywheels alone will not provide backup power to compensate fluctuation of power demands for a long period. Therefore, the flywheels should be associated with batteries or diesel generators. Some research works have been presented on the use of flywheel in different applications. For example, they have been analyzed to wind energy systems where the control and simulation of flywheel energy storage for a wind diesel power system was accomplished in Ref. [28]. For space applications, a control technique for charge and discharge operation modes for flywheel energy storage system was presented [29]. The use of flywheel based energy storage systems allows increasing the renewable energy penetration and in Ref. [30], the review for flywheel application as well as their simulation for an isolated wind power system was carried out. Flywheels energy storage systems also find application in automotive powertrains and the types of transmission needed to connect the flywheel to the vehicle's driveline are well articulated in Ref. [31]. Flywheel energy storage systems have also attracted new interest for uninterruptable power supply (UPS) applications in a facility microgrid where they are used in securing critical loads during outages in a utility microgrid environment [32]. However, to the best of the authors' knowledge, application of flywheel for hybrid PV/diesel systems has not been presented in the existing literature.

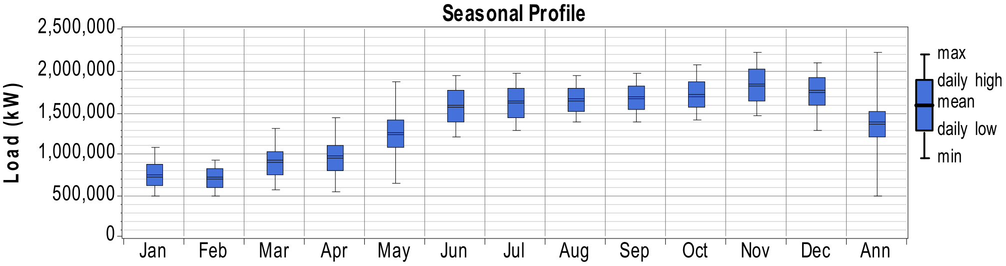

Fig. 2. Monthly load profile of Makkah.

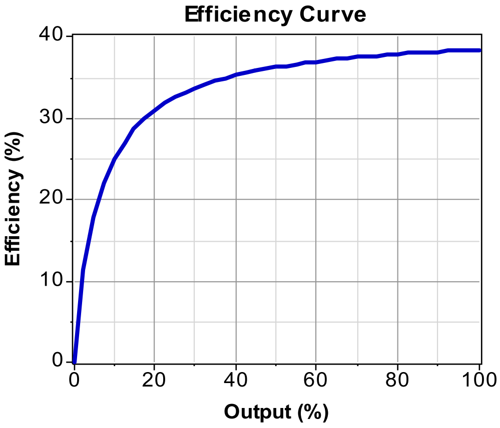

Fig. 3. Efficiency curve.

This paper aims to investigate PV/diesel system performance with flywheels energy storage for load demand in Makkah city, Saudi Arabia. Emphasis is put on the effect of flywheels usage on the performance and the economic benefits of the hybrid system.

2. The hybrid system under study

In order to carry out the economic analysis of a hybrid PV/diesel system with flywheel energy storage component incorporated, the model in Fig. 1 was created in the software. The software used is HOMER (Hybrid Optimization Model for Electric Renewables) which is publicly available and widely tested software developed by the National renewable energy laboratories mainly used for design and analysis of microgrid systems [33,34]. HOMER simulates all the possible system configurations and performs the energy balance computations for each feasible system configuration based on net present cost (NPC) in an ascending order [35].

Load profile of Makkah is presented in Fig. 2. From the load profile, it is shown that peak load in Makkah is 2213 MW with energy consumption of 32,962 MWh/day. The systems inputs and components are described in detail in Section 3.

3. System inputs and components

Five components are considered in the hybrid system, i.e. PV arrays, generators, inverters, batteries, and flywheel.

3.1. Diesel generator (DG)

A DG is characterized by its fuel consumption and efficiency. The fuel consumption characteristic is the amount of fuel consumed to produce electricity and is defined as [36]:

$$F_d = (a \cdot T_d + b \cdot P_d) \tag{1}$$

Table 1
Diesel generator data.

DG	
Lifetime	15,000 h
Min. load ratio	40%
Cost of investment	\$ 1521/kW
Cost of replacement	\$ 1521/kW
Cost of operation and maintenance	\$ 0.05/h

Table 2
PV data.

PV modules	
Lifetime	30 yr
Derating factor	90%
Cost of investment	\$ 1800/kW
Cost of replacement	\$ 1500/kW
Cost of operation and maintenance	\$ 10/kW/yr

where F_d, T_d, P_d, a and b denote the DG's fuel consumption rate (L/h), the DG capacity, the DG output, the fuel intercept coefficient (L/kWh), and the fuel slope (L/kWh), respectively. In Eq. (1), the DG is assumed to be run in a particular time step. If the DG is not running in a particular time step, then the fuel consumption for that time step is zero. The DG fuel intercept coefficient and slope are taken from its performance data and fuel consumption curve, which give a fuel intercept coefficient of 0.01609 L/kWh and the fuel slope of 0.2486 L/kWh.

The efficiency curve can be generated using the following formula:

$$\eta_d = \frac{3600 \cdot P_d}{\rho_f \cdot (a \cdot T_d + b \cdot P_d) \cdot LHV_f} \tag{2}$$

where η_d, ρ_f, and LHV_f are the DG's electrical efficiency (%), the fuel density (kg/m^3), and the lower heating value of fuel, respectively. In this study, the diesel fuel is assumed to have a density of 820 kg/m^3 and a heating lower value of $LHV_f = 43.2$ MJ/kg. Fig. 3 presents the DG efficiency curve. It is clearly shown that the DG efficiency is 38.39% at full load ($P_d = 100\%$), 36.19% at 50% load, 30.88% at 20% load, and 17.82% at 5% load.

In the simulation, 7 groups of generators with 80 MW/unit DG are employed in order to meet the load demand. The DG data is summarized in Table 1. The fixed capital investment for the DG was \$ 1521/kW, based on sale of used DGs. This cost includes the direct costs associated with installation and labor in Saudi Arabia as used in Refs. [37,38].

3.2. PV modules

The initial PV array is sized based on the peak load demand. The PV size can be either increase (over-sizing) or decrease (under-sizing) which depends on the amounts of unmet electric load and renewable fraction set in the design. The PV data used in the simulation are provided in Table 2. The PV modules lifetime was set at 30 years. The average price of the PV modules, including the installation cost, was set at \$ 1800/kW [39], while the O&M cost was estimated to be \$ 10/kW/yr.

3.3. Inverter

The inverter size is rated based on the PV size to maximize the quantity of energy which will be harvested by the inverter from the

Table 3
Inverter data.

Inverter	
Lifetime	30 yr
Efficiency	90%
Cost of investment	\$ 400/kW
Cost of replacement	\$ 375/kW
Cost of operation and maintenance	\$ 20/yr

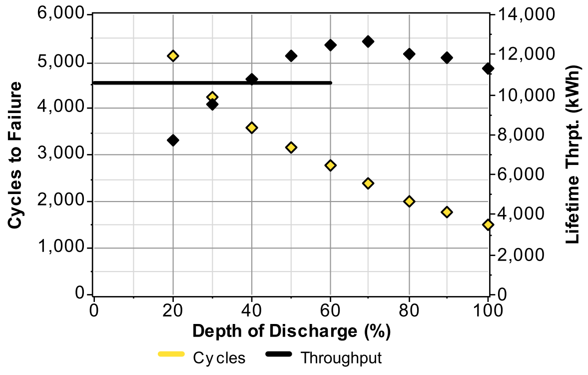

Fig. 4. Lifetime curve.

PV arrays. A constant R is generally used to express the PV size compared to the inverter size, defined as

$$R = \frac{the\ PV\ size}{the\ inverter\ size} \tag{3}$$

The inverter is frequently sized equal to or less than the PV size ($R \geq 1.00$) because the PV does not always produce its full rated power. The consideration to use a smaller size inverter is to minimize the inverter cost. However, most PV inverters cannot produce the reactive power. Following the new regulations adopted in the EU countries, inverters will need to be able to supply the reactive power. In such a case, the PV inverters should be oversized in relation to the PV arrays in order to deliver the required reactive power without reducing active power production. It was also reported that oversized (30%) inverters is the optimal size at power factor of 1 if all economic aspects are taken into account [40].

A brief summary on the data of inverter is presented in Table 3. The inverter lifetime was set at 30 years, which is the life expectancy for utility scale inverter recommended by IEA [41].

3.4. Battery

The type of battery used is Surrette 4 KS25P type which is a 4 V deep cycle battery rated at 1900 Ah for 100 h of operation. The battery life is limited by throughput. It assumes that the battery will require replacement after a fixed amount of energy cycles through the battery, regardless of the depth of the individual charge–discharge cycles. The battery lifetime is calculated by using the battery lifetime throughput. The battery's safe operating state of charge (SOC) is between 40% and 100%. The battery lifetime throughput is 10,569 kWh and its lifetime is 12 years when operated within the safe region. The battery lifetime will be shortened if it is operated below the SOC of 40% or over DOD of 60%, as illustrated in Fig. 4. The data of battery is provided in Table 4. Twelve 4-V batteries were connected in series to form a 48 V string, while strings were connected in parallel to form a battery bank.

Table 4
Battery data.

Battery	
Type	Surrette 4 KS25P
Lifetime	12 yr
Batteries per string	12
Voltage	4 V (48 V)
Capacity	1900 Ah
Cost of investment	$ 1200/quantity
Cost of replacement	$ 1200/quantity
Cost of operation and maintenance	$ 60/yr

Table 5
Flywheel data.

Flywheel	
Type	PowerStore-500
Lifetime	20 yr
Charge/discharge capacity	500 kW
Cost of investment	$ 400,000/quantity
Cost of replacement	$ 200,000/quantity
Cost of operation and maintenance	$ 8000/yr

3.5. Flywheel

A flywheel, as an energy storage system, can store and deliver electrical energy for a short period without recharging. It is one of the energy storage mechanisms which is suitable for medium scale renewable energy systems such as solar and wind [42]. They are also found for wide application in power continuity and power quality control such as power variations and interruptions in wind energy systems, by providing energy backup capabilities [43]. A flywheel energy storage system generally has the storage time in the range between 5 s and 30 s. The charge and discharge conditions of a flywheel can occur at high rates for many cycles. The flywheel uses mechanical processes to store the electrical energy. The output of flywheel is kinetic energy of the spinning mass (rotor) which is converted from electrical energy supplied by the sources. The flywheel stores energy by accelerating the rotor to a very high speed, while it releases energy by decelerating the rotor to slow down until eventually coming to a complete stop.

The stored energy is determined by the mass and the angular velocity of the rotor. The equation for stored kinetic energy is

$$E = \frac{1}{2} J \omega^2 \tag{4}$$

where ω is the rotor angular velocity and J represents the moment of inertia which is defined as

$$J = kmr^2 \tag{5}$$

where m is rotor mass (kg), r is rotor radius (m), and k is an inertial constant depending on the rotor shape.

For example, the PowerStore-500 flywheel has charge/discharge capacity of 500 kW and the energy content of 18 MWs at 100% SOC. The flywheel should provide time to start-up DGs. The backup period for the flywheel is about 30 s, which is enough time for a DG to start-up and synchronize with the system. The data of flywheel is given in Table 5.

Table 6
Specified parameters of systems.

Flywheel charge/discharge capacity	250,000	kW
Inverter size	2,860,000	kW
DG size	2,200,000	kW
PV size	2,200,000	kW
Battery nominal capacity	186,960	kWh
Battery maximum charge/discharge capacity	7426	kW
Renewable fraction	33	%
Diesel fuel price	1.09	$/L

Table 7
Systems without flywheels.

	DG	PV/DG	PV/DG/Bat
Diesel consumption (L/yr)	3,212,823,048	2,362,475,796	2,358,859,396
CO_2 emissions (kg/yr)	8,460,420,608	6,221,176,320	6,211,653,120
Total NPC ($)	78,451,802,112	65,882,980,352	65,848,451,072
COE ($/kWh)	0.463	0.389	0.388

3.6. *Total annual cost*

Total annual cost represents the annual value of the total NPC, which can be expressed as

$$C_{ann,tot} = \mathrm{CRF}(i, R_{proj}) C_{NPC,tot} \tag{6}$$

where $C_{NPC,tot}$ is the total NPC, i is annual real interest rate (%), R_{proj} is the project lifetime (yr), and CRF is the capital recovery factor. The NPC is the project costs present value minus all profits over its expected lifetime. In this case, the costs of capital, replacement, operation and maintenance are included in the project costs. Revenues include the salvage value. The nominal interest rate minus inflation over the year is defined as the annual real interest rate,

$$i = \frac{i' - f}{1 + f} \tag{7}$$

where f is annual inflation rate and i' is the nominal interest rate. Then, we can define the CRF as

$$\mathrm{CRF}(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{8}$$

where i is the interest rate and N is number of years.

3.7. *Levelized cost of energy (COE)*

Cost of energy (COE) is a ratio between annual electricity cost and the total electric load served by the system, given by

$$\mathrm{COE} = \frac{C_{ann,tot}}{E_{served}} \tag{9}$$

where $C_{ann,tot}$ = total annual cost, while E_{served} = total electrical load served (kWh/yr).

The levelized cost of electricity (LCOE) includes capital costs, depreciation, operation, maintenance, management etc. LCOE allows a direct comparison of the costs of all types of electricity generation. LCOE of all forms of renewable energy has decreased considerably in the last five years [44].

4. Simulation results and discussions

Firstly, the simulation using HOMER is performed for hybrid systems with or without battery and compared to the DG system to compensate for the peak load. The systems are further simulated with consideration of flywheel storage devices in order to assess the flywheel's contribution in reducing the LCOE and carbon emissions.

Table 8
Systems with flywheels.

	DG/FW	PV/DG/FW	PV/DG/Bat/FW
Diesel consumption (L/yr)	3,212,338,176	2,338,807,296	2,336,093,440
CO_2 emissions (kg/yr)	8,459,144,192	6,158,849,024	6,151,703,552
Total NPC ($)	76,474,064,896	62,785,138,688	62,772,746,624
COE ($/kWh)	0.451	0.370	0.369

Table 9
Net savings when the flywheels are included in the power system.

	From DG to DG/FW	From PV/DG to PV/DG/FW	From PV/DG/Bat to PV/DG/Bat/FW
Diesel consumption (L/yr)	484,872	23,668,500	22,765,956
CO_2 emissions (kg/yr)	1,276,416	62,327,296	59,949,568
Total NPC ($)	1,977,737,216	3,097,841,664	3,075,704,448
COE ($/kWh)	0.012	0.019	0.019

In this paper, the simulation is performed using 5% annual real interest rate and currently average diesel price in the world of 1.09 $/L. The system parameters used are shown in Table 6.

Ratio of PV to inverter size is $R = 1.0/1.3$, as shown in Table 6, in order to guarantee the availability of reactive power for the whole year. It will also maximize the energy harvested from the PV arrays and hence reduce total operating costs of DGs. The DG size is designed equal to the peak load in order to meet all load demand.

Six system configurations with and without flywheels (FW) have been considered for analysis including; stand-alone DG, PV/DG, PV/DG/Bat, which are analyzed first; the DG/FW, PV/DG/FW and PV/DG/Bat/FW analyzed afterwards. Table 7 shows the diesel consumption, CO_2 emission, NPC and the COE for the DG, PV/DG, PV/DG/Bat systems.

From Table 7, it is clear that the diesel consumption is high, about 3.213 billion L/yr when the generator is the only source of energy. With a PV/DG system, the diesel consumption reduces to about 2.362 billion L/yr due to incorporation of a PV system (with PV penetration = 33%). The diesel consumption is seen to decline further to about 2.359 billion L/yr as a result of hybridizing the PV/DG with battery as backup system and 3,616,400 L/yr are saved. Correspondingly, with the inclusion of a battery storage device, the COE is also observed to decline from 0.389 to 0.388 $/kWh. This is

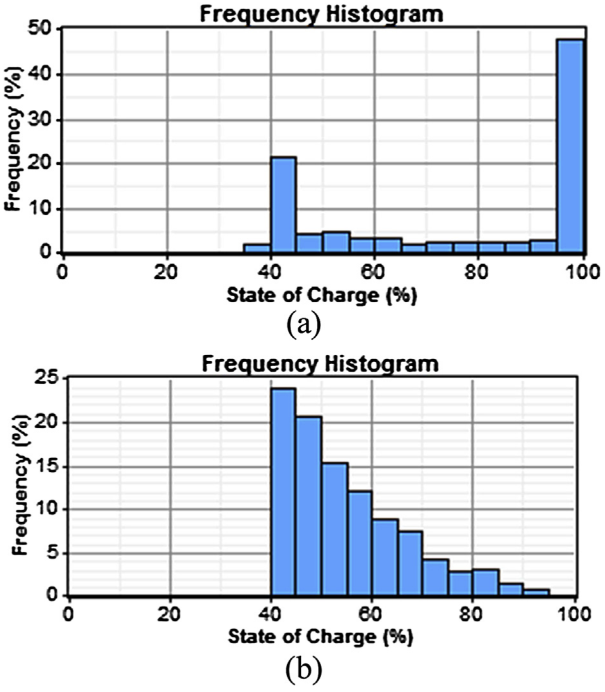

Fig. 5. Performance of the batteries: (a) without flywheels, and (b) with flywheels.

Table 10
Performance of batteries.

	PV/DG/Bat	PV/DG/Bat/FW
Energy in	4,282,744 kWh/yr	10,323,232 kWh/yr
Energy out	3,427,545 kWh/yr	8,323,816 kWh/yr
Annual throughput	3,832,109 kWh/yr	9,306,308 kWh/yr

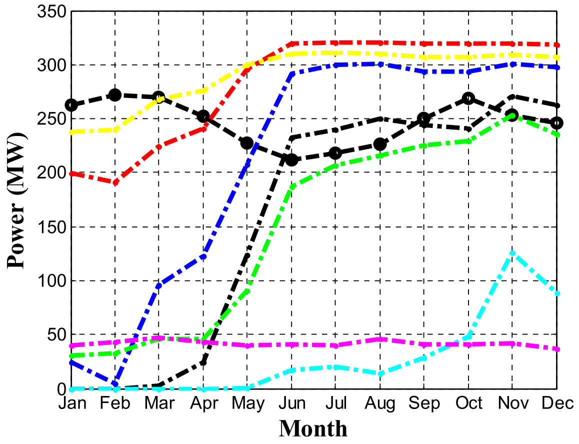

Fig. 6. Monthly average power generation (PV = 1.1 GW).
(--o PV, -- Gen1, -- Gen2, -- Gen3, -- Gen4, -- Gen5, -- Gen6, -- Gen7)

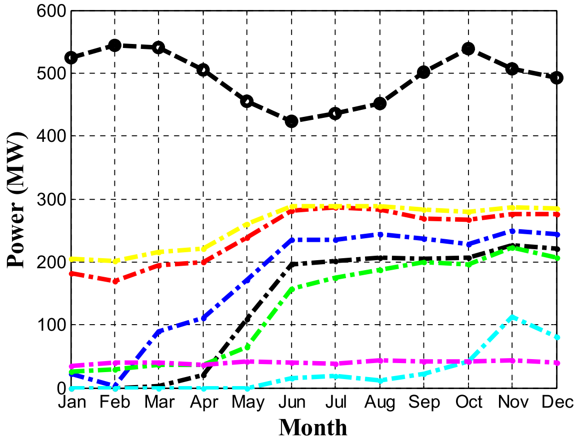

Fig. 8. Monthly average PV power generation (PV = 2.2 GW).
(--o PV, -- Gen1, -- Gen2, -- Gen3, -- Gen4, -- Gen5, -- Gen6, -- Gen7)

due to the fact that during the time the PV is not supplying energy due to absence of the sun, mainly during night time, the energy requirement gap is bridged by using electricity generated from the DG. However, when the battery storage element is installed the excess energy generated by the PV is stored and released at a time of necessity when the PV is not generating energy.

In terms of NPC, it can be observed that with the introduction of the solar PV (with PV penetration = 33%) to make a hybrid PV/DG system, the NPC decreases from about 78.452 to 65.883 billion $. This indicated that deploying the renewable energy technology reduces the cost of energy. Moreover, the payback period of initial investment of renewable based hybrid systems will be reduced due to the decreasing PV module costs, increasing diesel fuel costs and CO_2 emission trading system [45]. Further installation the backup system (battery) has demonstrated a decrease in the NPC to 65.848 billion $, leading to a saving of about 34.529 million $, as a result of reduced diesel consumption.

Similar observations can be drawn from Table 7 regarding CO_2 emissions. The installation of PV resulted in to the decrease of emissions from 8460 million ton CO_2/yr for DGs only to 6221 million ton CO_2/yr for a hybrid PV/DG system, indicating the primary objective of installing renewable energy. Perera et al. observed that it is essential to bear a higher initial capital cost when it comes to renewable energy sources although the operational and maintenance costs are low [46]. It is also noted that about 2.25 million ton CO_2/yr are saved when the batteries are installed.

Table 8 shows the results when the flywheel is integrated into the system.

As power buffer, the flywheels give chance to DGs to be turned off and remain off during a short period. The flywheels also provide operating reserve, so they can reduce the need for the DGs to operate at small loads. This condition will save diesel fuels and O&M expenses. As a result, the flywheels decrease CO_2 production, diesel fuel consumption, the total NPC, and the COE of stand-alone DG, PV/DG, or PV/DG/Bat systems by minimizing operating time of diesel generators.

To verify the contribution of flywheel storage technology in cost an emission saving, the difference between the results in Table 7 (without flywheel) and Table 8 (with flywheel) is computed by subtracting the values in Table 8 from those in Table 7. The net savings in terms of diesel consumption, CO_2 emission, NPC and the COE, when the flywheels are installed are summarized in Table 9. It is clear from Table 9 that flywheels, when used, lead to a considerable reduction in the diesel usage as 484,872 L/yr of diesel are saved when a DG/FW system is operated. It is further observed that with a PV/DG/Bat/FW the diesel saved is 26,382,356 L/yr which is

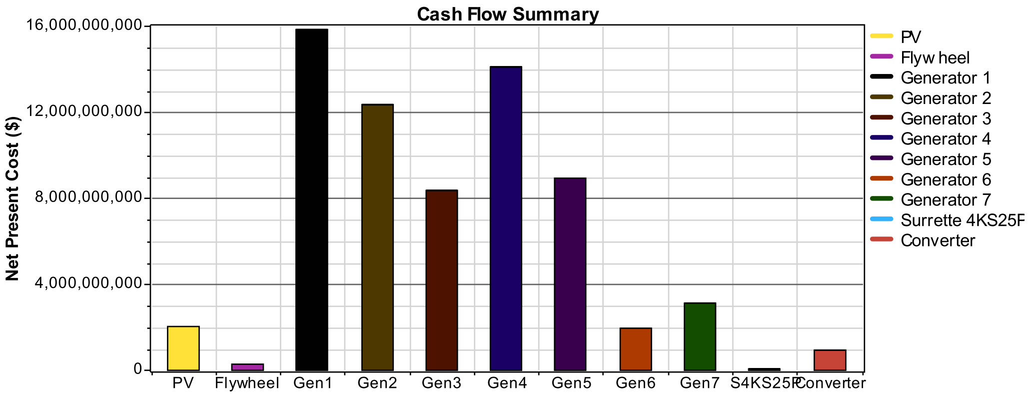

Fig. 7. Cash flow summary.

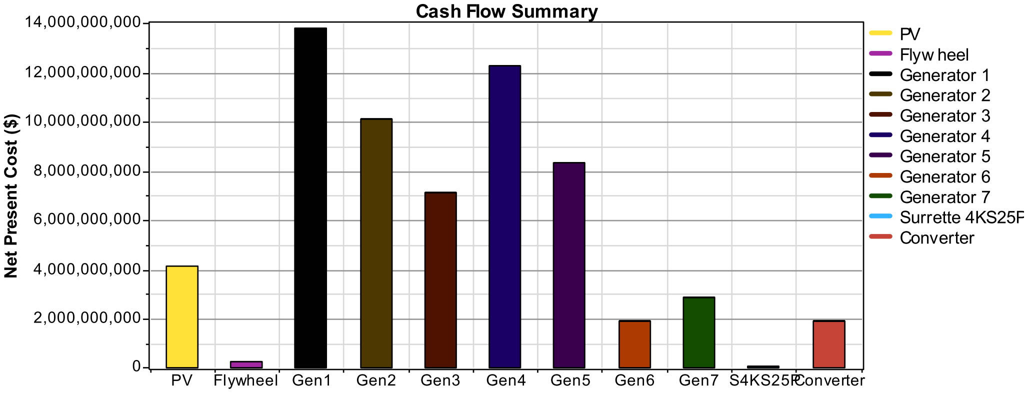

Fig. 9. Cash flow summary.

about seven times that saved by a PV/DG/Bat (3,616,400 L/yr saved). This proves the ability of the flywheel to boost the utilization of the battery storage system as the contribution of the flywheel is only 484,872 L/yr out of 26,382,356 L/yr. The rest is the as a results of increased utilization of the battery.

For the system with batteries (PV/DG/Bat), flywheels support the batteries to compensate for the renewable energy output fluctuation. The batteries charge/discharge cycles have important effects on the system performance. The presence of flywheels can enhance the batteries storage time and hence increase their utilization time, as presented in Fig. 5. For the longer storage time, charging energy of the batteries increases and results in a larger energy throughput. Performances of the batteries in the PV/DG/Bat system with and without flywheels are shown in Table 10.

In order to further study PV/DG hybrid system with batteries and flywheels energy storage with regard to cash flows and renewable energy penetration (REP) levels, two options of configuration are considered:

1. Option 1: PV (1.1 GW) with batteries, flywheels, and DGs
2. Option 2: PV (2.2 GW) with batteries, flywheels, and DGs

Option 1: PV (1.1 GW) with batteries, flywheels, and DGs

The simulation results show that this system gives total NPC of $ 68,114,919,424 and CO_2 emission of 7,145,655,808 kg/yr. The system COE is $ 0.402/kWh with the PV penetration of 17%.

Monthly average power generation and cash flow summary are then shown in Figs. 6 and 7. We can see from Fig. 6 that in the month of January and February when the power generated from PV is high, the power generated from the DGs is low because most of the energy requirement is satisfied by clean energy from PV. Fig. 7 shows that the generator contributes a bigger portion to the total NPC of the project mainly from generator 1, 2 and 4. However, the flywheel has a smaller value of NPC though it is higher than that of the battery.

Option 2: PV (2.2 GW) with batteries, flywheels, and DGs

The simulation results show that this system gives total NPC of $ 62,782,746,624 and CO_2 emission of 6,151,703,552 kg/yr. The system COE is $ 0.370/kWh with the PV penetration of 33%. Figs. 8 and 9 show monthly average power generation and cash flow summary. We can observe from Figs. 8 and 9 that with the capacity of PV doubled, the power generated by DGs reduced significantly from 83% to 67% when compared to the system with PV capacity of 1.1 GW.

Furthermore, the summary of hybrid PV/DG system performance with batteries and flywheels are presented in Table 11. We can observe that the unmet load is 0% but the excess electricity is 0.45 and 4.72% of the generated value. This excess electricity can be sold if the system is connected to the grid using a net metering plan [47].

Table 11
Hybrid PV/DG systems with batteries and flywheels performance.

Config.	Unmet load (%)	Excess elect. (%)	NPC ($)	COE ($/kWh)	PV penet. (%)	CO_2 emissions (kg/yr)
Option 1	0%	0.45	68,114,919,424	0.402	17	7,145,655,808
Option 2	0%	4.72	62,782,746,624	0.370	33	6,151,703,552

5. Conclusion

An economic analysis of PV/diesel hybrid system performance with flywheel energy storage was presented based on power generation, energy cost, and net present cost. For this analysis, three different system configurations, i.e. diesel/flywheel hybrid system, PV/diesel/flywheel hybrid system, and PV/diesel/battery/flywheel hybrid system has been simulated using HOMER software. It has been clearly demonstrated from the simulation that the PV/diesel/battery/flywheel hybrid system has the lowest COE and CO_2 emissions. In order to analyze the performance of PV/diesel/battery/flywheel hybrid system, two options of PV array size have been considered, that is, 1.1 GW and 2.2 GW. The PV/diesel/battery/flywheel hybrid system using 2.2 GW PV array size has the lowest COE with 33% renewable penetration. As a conclusion, the PV/diesel system with flywheel is more economical than the PV/diesel system without flywheel energy storage. The use of flywheels decreases CO_2 emissions, diesel fuel consumption, the total NPC, and the COE of the system by minimizing diesel generators operation. In addition, the flywheels not only enhance the batteries storage time but also increase their utilization time.

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