PHOTOVOLTAIC AND GAS TURBINE SYSTEM FOR PEAK-DEMAND APPLICATIONS

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ABSTRACT

A computer simulation model of the behaviour of a photovoltaic (PV) gas turbine hybrid system with a compressed air storage is developed in order to evaluate its performance and predict the total energy-conversion efficiency and the incurred costs under various operating conditions. This integrated PV and gas turbine hybrid plant produces approximately 140% more power per unit of energy consumed compared with conventional gas turbine plants. In addition, lower rates of pollutant emissions to the atmosphere are achieved.

Key words: *Photovoltaic, Computer Simulation, Gas Turbines, Energy Conversion Efficiency*

INTRODUCTION

Stored energy, e.g. via batteries, elevated water reservoirs, super-conducting magnets and flywheels, can be recovered for use during periods of shortage and/or peak demand. This increases the reliability of the power supply and reduces the need for the less cost-efficient peaking units. Generally, electric utilities need peak load plants to be readily available as stand-by for rapid and simple operation. At present, diesel engines, traditional gas turbine (GT) and pumped hydropower storage (PHPS) schemes are used to meet the growing peak demands. The PHPS, which is a potential energy storage system, represents the most economic means to store energy presently available to electric utilities. However, PHPS plants are very expensive to install, require suitable sites and long lead times for construction [1]. The compressed air storage (CAES) is also a potential energy storage, in which electrical energy in excess of the demand is used to compress air, which is stored in a reservoir for later use in a gas turbine to generate electricity. CAES has the common advantages of peak load gas turbine power plant and of the pumped storage schemes. Therefore, such plants are being recognised as a technically feasible and economically attractive option for load management [2,3]. A CAES system usually has a relatively (i) high efficiency, (ii) low capital cost as well as (iii) larger energy density compared with other technologies [1,3,4].

At present, many countries around the world, e.g. Jordan, use conventional GTs to meet any shortages in available electricity supplies occurring during an emergency or during the peak load demand periods. Such systems, especially those operating in an open or simple cycle, have the disadvantage of being least efficient and so the unit cost of generated electricity is relatively high. For example, in Jordan, gas turbines used for this purpose consumed about $25x10^3$ tonnes of diesel fuel, but supplied less than 82 GWh, i.e. 1.2%, of electricity generated in 2001 [5]. The average efficiency of GT peaking plants, in Jordan, over the last five years, was in the range of 24-27% [6,7]. This can be attributed to many reasons, such as operation mode, poor maintenance, engine size and age. But the most important factor is that the load control for conventional gas turbine plants is accomplished by adjustment of the fuel's flow rate into the combustion chamber, while the airflow remains invariable. Such adjustments result in excessive rates of fuel consumption, especially at partial loads when the TIT is decreased [8]. However, the integrated CAES gas turbine has its airflow adjusted according to the power generation requirement, while the TIT remains constant. Thus, the specific fuel consumption during partial-load operation is significantly improved [4]. Hence, the final unit cost of produced electricity will be lower.

Unit cost of the produced electricity and the gas emissions that would otherwise arise from conventional generators could be reduced by employing a hybrid system that uses a renewable energy source, such as solar energy. An example of a solar-fuel hybrid system is the integration of a solar air heater unit with a gas turbine power generator [9,10]. In this solar-fuel hybrid system, a solar central receiver plant heats the compressed air, which is then directed to a combustor. It was found that, by using such technique, the compressed air temperature is doubled and the plant's overall efficiency increased significantly. Another type of solar-fuel hybrid system is the one that uses PV panels to generate electricity in parallel with conventional generators. Many studies were conducted to analyse the performance and feasibility of existing PV hybrid systems. It was shown that PV hybrid systems are practical and economic alternatives for many applications [11,12,13]. Incorporation of the PV array reduces the rate of fuel consumption, maintenance costs, and adverse impacts on

the environment. Although the initial cost of the integrated PV system, with the gas turbine, is typically higher than that of conventional generators, the life-cycle cost of the former can be significantly less expensive, particularly when environmental impacts are considered.
The aim of the present study is to investigate the performance of an integrated photovoltaic-gas turbine (PVGT) plant, with compressed air storage. The PV electric generator is used to run an air compressor instead of consuming some of the produced shaft power; the compressor being directly coupled with the turbine. A computer program was developed for predicting the performance of three cases, these are:

- basic system of conventional GT;
- standard CAES; and
- proposed PVGT scheme.

It is not the intention of this investigation to address other critical issues relating to off-design operation, compressor or turbine design and PV technology: rather guidance information concerning the proposed hybrid system is deduced so that its overall performance can be compared with those of other basic peaking-systems.

THE PROPOSED HYBRID PVGT SYSTEM

This system, as in CAES, has two separate operating modes – see Figure 1. Compression, i.e. charging the reservoir, and expansion, i.e. discharging the reservoir. In the storage-charging mode, the motor/generator is used as motor and drives the compressor, which delivers high-pressure air into the reservoir. The latter may be aboveground, e.g. vessel, or underground, e.g. cavern or porous media. In this mode the expander is disconnected and the plant consuming power from the PV panel. In the generation mode, when electricity is required by the grid, the expander is connected by applying the clutch to the motor/generator, which acts as a generator to produce electricity.

A combination of electricity generation by means of PV, which used to drive the air compressor and gas turbine in regions where conventional energy sources are expensive or rarely available, is expected to improve the prospects for harnessing the free and clean solar energy in a more economic way. This new approach involves the use of the following main components:

- gas turbine engine.
- PV array and DC/AC inverter.
- reservoir to store the compressed air.

The integration of these items together can reduce the heat rate (HR) of the generation system significantly. This would reduce the cost of the generated electricity compared with what can be achieved with stand-alone conventional gas turbines. In addition, lower rates of polluting emissions per unit of electricity produced would be released to the environment.

This newly proposed generation system is more likely to be suitable for dry and arid areas, where fresh water is scarce. The PV panel will convert the solar energy into electricity. The latter is used to empower the motor/generator, which drives the compressor in the charging mode, i.e. during daytime. When electricity is required by the grid during peak demand, the compressed air is allowed to flow into the combustor. In which liquid or gaseous fuel is added to raise the temperature up to the design point. Then, high pressure and temperature gases expand in the turbine, which is connected by applying the clutch to the motor/generator. The latter, in this mode, acts as generator and produce electricity.

Theory and Performance Modelling

In their continuous planning for load growth, electricity utilities search for the most economic generation schemes. But this will be subject to a number of constraints, such as the type of fuel available, peak-to-base demand ratio and compliance with national environmental standards. To assess the behaviour of a power plant over its expected ranges of operation, appropriate mathematical models, which can predict the performance under both design-point and off-design or part-load operating conditions have been developed. In this investigation the performance analysis of various peaking units is discussed. For the two systems using compressed air storage, the main operating variable is the compressor pressure ratio (PR), which indicates the pressure level in the reservoir, while the TIT and TET remain invariant. Solar radiation is also another variable, but for PV computation. The charging-discharging time ratio, which illustrates the air mass flow rate during generation mode corresponding to a specified rate during compression, is constant.

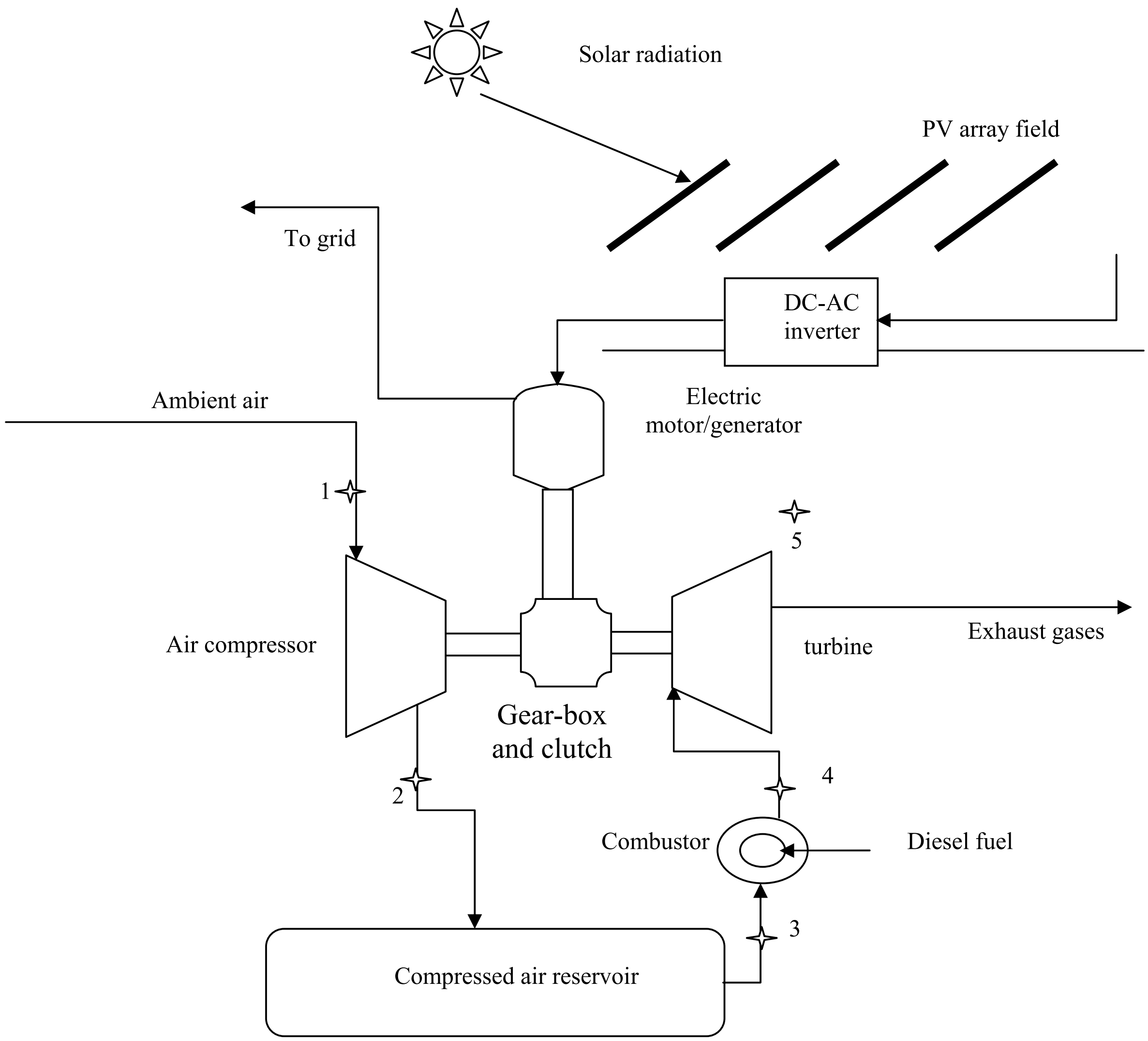

Fig. 1. The proposed PV-Gas turbine hybrid system.

Because the CAES system is a dual-purpose plant, i.e. energy storage and peak power generation, having two sources of energy inputs during charging and discharging phases, which are of different qualities, the adopted criteria for evaluating such plants differ from that usually used for conventional GT [3,4,8]. More specifically, the specific fuel consumption or HR cannot identify the thermodynamic merits of the CAES plant as in standard GT power stations. Hence the primary energy efficiency has been adopted.

The thermal power analysis of the PVGT plant was performed taking into consideration the compressor and turbine efficiencies, electric conversion efficiency of the motor-generator. Pressure losses in the compressor intake, reservoir piping, combustor and turbine exhaust ducts were also considered as well as the variations of the specific heats of air and combustion products. These calculations were carried out by means of a specially designed computer programme. This model is based also on energy and flow matching of the turbomachinery components, i.e. the components are aerodynamically coupled along the flow satisfying mass continuity and they are coupled by the engine shaft, so energy balance exists. The main points of calculation procedure for the proposed system, with reference to Figure 1, using basic relations are listed below.

PV Array System

Various types of PV power generation systems are currently operating at different countries and many papers were published concerning their performance [14-17]. Other researchers studied the long-term efficiency profile under actual solar radiation conditions of a solar tracking flat PV panel [18]. They presented the monthly energy production, system capacity factor, and field efficiency for a year of plant operation. From the work of Jennings and Milne, an empirical relationship between the daily average radiation and the overall efficiency of the PV system was developed, as follows:

$$\eta_{PV} = 0.0435 Ln(I_r) - 0.004 \quad (1)$$

Different techniques of solar radiation concentration can be used to reduce the capital cost of a PV power generation system. By using optical concentrators to focus sun light onto solar cell the PV array and consequently its cost can be reduced. Although a more expensive solar cell is used, it can still be cost effective due to its higher efficiency [11,19]. One of the most adaptable concentration methods is the single axis tracking parabolic trough [19,20]. In this system most of the solar cells are replaced by a glass mirror, which cost far less than flat PV panel. The remaining few solar cells in the system, at the focal line of the trough, represent relatively small part of the total system cost. This means that expensive but more efficient cells can be used without economic penalty. However, the PV-trough system is still not feasible in some applications due its high capital cost. The other promising concentration technology is the point focus system, which uses a reflective solar tracking dish or Fresnel lens of high-efficiency silicon concentrator PV cells [19]. As shown in Table 1, the expected capital and O&M costs of point focus system are significantly below the other PV systems and can compete with those incurred in conventional GT's in the long run.

Gas turbine unit

Compressor

Standard compressor is used, without inter- or after-coolers. The basic assumption is that the energy consumed by the compressor during off-peak operation equals energy generated by PV array during the day. Then,

$$W_c \times hr = I_r \times \eta_{PV} \times A_{PV} \quad (2)$$

From eqn. (2), the required area of PV array (A_{PV}) and the generated power during day-time are evaluated.

Combustor

Single stage combustion is proposed. The mass flow rate across the combustor equals the total flow rates of fuel and air. The heat input during the combustion of diesel fuel equals to:

$$Q_{in} = \dot{m}_a (1 + FA) C_{p_g} (T_4 - T_3) \quad (3)$$

Turbine

There is no reheat and the polytropic efficiency is taken constant, with respect to specific heat, for all stages in order to simplify calculations, but without affecting the accuracy of final results. The pressure of gases after the combustor is evaluated by considering pressure drop in the reservoir, piping and burner, thus

$$P_4 = P_2 - (\Delta P_r + \Delta P_p + \Delta P_b) \quad (4)$$

In case of a conventional GT, pressure drop in air reservoir (ΔP_r) and piping (ΔP_p) are eliminated from equation (4). Turbine exit pressure is evaluated by considering the effect of pressure drop in the exhaust:

$$P_5 = P_1 (1 + \Delta P_e) \quad (5)$$

Table 1. Main Design Factors for The GT Engine and PV System

AMBIENT CONDITIONS	DESIGN VALUE
. temperature (°C)	15
. pressure (kPa)	101.3
. relative humidity (%)	60
GAS TURBINE MODEL	GT 6001 B (single shaft and simple cycle)
-***Design output*** (MW_e)	40
-***Heat rate*** (kJ/kWh)	11,480
-***Compressor***	
. pressure ratio	11.8
. air mass flow rate (kg/s)	136.95
. isentropic efficiency (%)	85
. leakage fraction (%)	0.2
-*Combustor*	
. combustion efficiency (%)	99.5
. pressure drop (kPa)	3
. actual fuel/air ratio	0.02
-*Turbine expander*	
. inlet pressure (kPa)	1188
. inlet temperature (°C)	1160
. exhaust temperature (°C)	574
. isentropic efficiency (%)	85
-***Electric generator*** (dual purpose motor/generator)	
. generator's efficiency (%)	98
-***Average costs***	
. capital investment ($/kW)	450
. annual O&M ($\$/kW_{\text{installed per year}}$)	40
. diesel fuel ($/kg)	0.2
. unit price of generated electricity ($/kWh)	0.085
COMPRESSED AIR STORAGE SYSTEM	
. pressure drop (kPa)	25
. air temperature (°C)	350
THERMODYNAMIC PROPERTIES	
. specific heat at constant pressure (kJ/kg K)	1.005 & 1.091 for air and combustion gases
. specific heat ratios	1.4 & 1.33 for air and combustion gases
PV SYSTEM	
-PV-flat panel (two-axis tracking)	
. capital cost ($/kW)	4140
. annual O&M ($\$/kW_{\text{installed per year}}$)	785
. average efficiency (%)	9
. generated power (kW/m^2 of module area)	0.13
-PV-trough (single-axis tracking)	
. capital cost ($/kW)	8880
. annual O&M ($\$/kW_{\text{installed per year}}$)	120
. average efficiency (%)	14
. generated power (kW/m^2 of module area)	0.117
-PV-point focus *(two-axis tracking)*	
. capital cost ($/kW)	2360
. annual O&M ($\$/kW_{\text{installed per year}}$)	28
. average efficiency (%)	17
. generated power (kW/m^2 of module area)	0.145

Overall performance

The energy ratio, ER, is unique for CAES plants, expressing the ratio of pumping energy at off-peak period to the generated energy during the peak demand. Thus, it has been used in addition to E_{gen}, which equals the net electric-power output, and primary efficiency as main indicators for evaluation of the performance of such systems.

$$ER = \frac{E_m}{E_{gen}} \quad (6)$$

$$E_{gen(GT)} = (W_t - W_c) \times \eta_{g-m} \quad (7)$$

In case of the PVGT system, a PV unit runs the compressor, therefore during peak hours all the turbine work is considered as net output:

$$E_{gen(PVGT)} = W_t \times \eta_{g-m} \quad (8)$$

Then heat rate is evaluated by using the basic definition and as follows:

$$HR = \frac{Q_{in} \times 3600}{E_{gen}} \quad (9)$$

Unit price of electricity produced, annual expenses of conventional GT and PVGT are evaluated from the following equations, respectively.

$$\mathrm{C_{eu}} = \left(\frac{\mathrm{C_{om}} + \mathrm{C_f}}{E_{gen}} \right) \quad (10)$$

$$C_{(GT)} = \left(C_{om(GT)} + C_f\right) \quad (11)$$

$$C_{(PVGT)} = \left(C_{om(PVGT)} + C_f\right) - C_{es} \quad (12)$$

CASE STUDY AND ASSUMPTIONS

For peak load applications, commonly medium size GTs' are employed, whereas for base load generation heavy-duty engines are used. But for emergency electric-power generation, smaller units are usually assigned to satisfy the required emergency-demand. In this study, the selected actual engine, GT 6001 B (PG 6541-B) from General Electric Power Systems, with a nominal rating of 40 MW_e, is an open cycle and single-shaft gas turbine. This engine is owned and operated, at present as standby and peaking unit in Jordan, by CEGCO and firing diesel fuel. In order to undertake a design-point analysis for the chosen GT plant, the practical data summarised in Table 1 were used. Such data were taken from the technical manuals of CEGCO and General Electric [21,22].

RESULTS AND DISCUSSION

Jordan lies in a region of high solar radiation level. The annual average solar radiation is between 6-8 kWh/m^2-day, which is among the highest in the world. The total radiation period is about 3000 hours, with an average daily of 8 hours [23]. This provides adequate energy for solar thermal and electrical applications such as the proposed PVGT system.

Based on the solar radiation data [24] and studied gas turbine engine, the required PV area was calculated around the year, as shown in Figure 2. Due to the high solar radiation during the period from June to August minimum PV area is required, to provide a certain output. Fortunately, the peak load always occurs during summer, i.e. July-August, due to the heavy use of air-conditioning and ventilation systems as a result of the dry climate and high temperatures Thus, all calculations were based on this minimum area of PV panels, i.e. 15×10^4 m^2. But it should be noted that, at present, such an area is very huge and there is no such plant exists elsewhere.

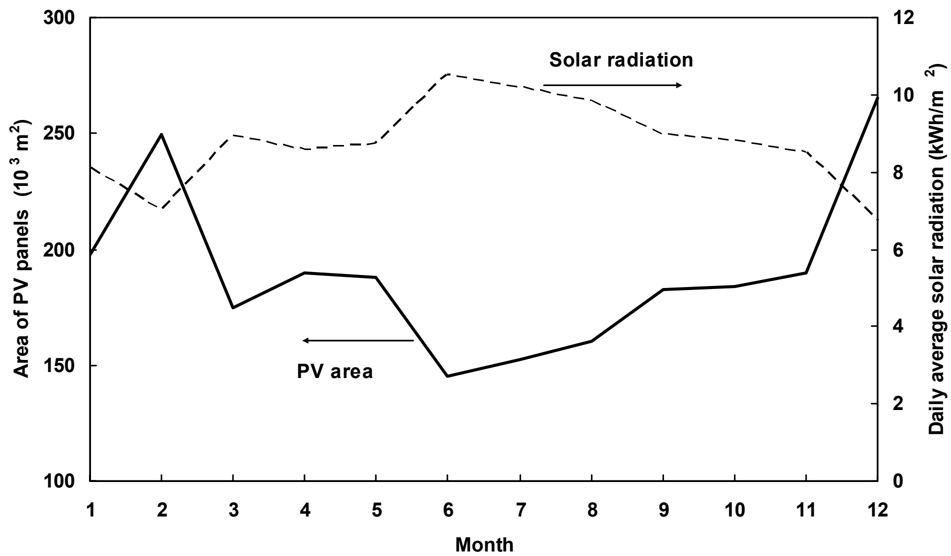

Fig. 2. Area of PV panel system required, around the year, to run the air compressor.

The main performance parameters are evaluated at the design point, using a specially designed computer program. Considering the engine will work on generation mode only during peak demand period, the charging time is full day and mass capacity of air storage system is sufficient to run the turbine for at least 3 hours. Efficiency and power ratio, which equals the output of the PVGT to that of GT, are demonstrated in Figure 3. It is obvious that PVGT has a lower efficiency of about 13%, in summer, whereas the efficiency of the conventional peaking GT is approximately twice that of PVGT. This can be attributed to the low conversion efficiency of PV panels available commercially in the international market [19]. But the PVGT has the common advantages of the peak load generating unit, compressed air storage scheme and renewable energy source. It generates, during the peak load period, approximately 2.5 times the electrical power as compared to conventional GT plants. In the latter more than 50% of the produced shaft work is used to drive the compressor and ER is between 0.7-0.8, depending on system configuration [3,4,8]. Thence, the proposed PVGT has the extra advantage of releasing some of the scarce capital investment, which will be needed for installing peak load power plants. This money can be used for the development and growth of other sectors of the national economy. Also, the more use of renewable energy will result in less negative environmental impacts. Moreover, it will reduce the huge cost of imported oil and so improve the national balance-of-payments. On the global level, increased rates of renewable energy and more rational utilisation of fossil fuels will lead to a higher ratio of crude oil reserves to production, as well as lower rates of pollutants emitted to the atmosphere.

Three types of PV systems were considered. These are: flat panel, parabolic trough and point focus. The accumulated cost of such systems, which include capital charge, fuel cost and O&M expenses, over the lifetime of generating unit, is presented in Figure 4. In the short term, the conventional GT has a low cost in the first few years because of relatively low initial cost compared with other peaking schemes. However, the proposed PVGT with point focus concentration PV system, at current prices, would have the lowest cost on the long run: after nearly 15 years it become cost effective. This is because more energy being produced from the PVGT per unit of air mass flow rate across the unit. The average HR for GT and PVGT are 12600 and 5500 kJ/kWh, respectively. In the case of flat and parabolic trough systems, the accumulated and O&M cost is very high because of its relatively low efficiency and huge area required to provide same output [25]. But, in general, these costs and financial performance of the proposed PVGT may be improved when operating time, as generating unit, extended beyond peak load period and/or cost and efficiency of PV panels become closer to those of peaking systems employed currently. Furthermore, the performance of CAES and PVGT technology can be improved significantly by using advanced gas turbines with reheat cycle and steam injection into the combustor by employing heat recovery steam generator. However, it should be remembered that lifetime for solar installations is often unknown and error in its assumption may produce misleading results.

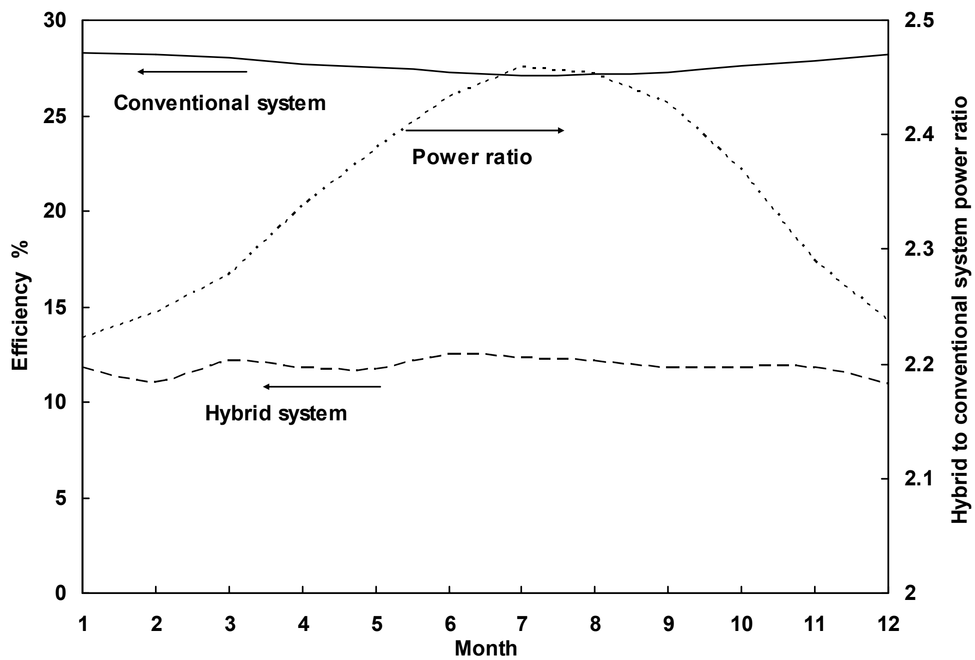

Fig. 3. Efficiencies and power ratios of a conventional GT and a PVGT system.

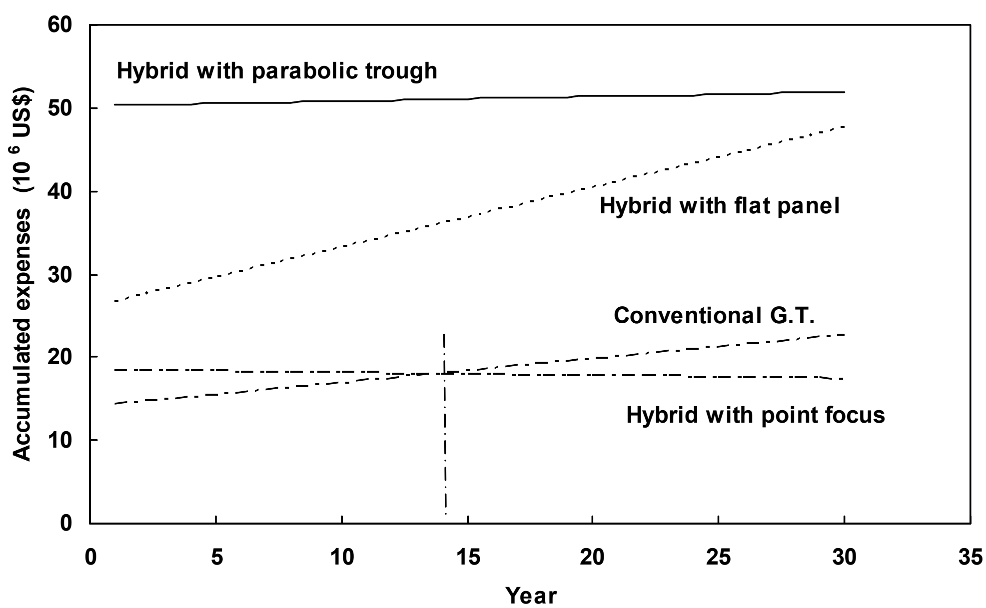

Fig. 4. Accumulated expenses of a conventional GT and three types of PV hybrid systems: flat panel, parabolic trough, and point focus.

The unit price of generated electricity from conventional GT and PVGT systems around the year is shown in Figure 5. It is clear that the electricity unit price incurred from GT is twice as that of the PVGT system. This is due to the elimination of compressor work during peak hours, which consequently results in surplus electricity. It is worth mentioning that the incurred electricity unit price from PVGT corresponds to those occurring in different base-load power stations [26].

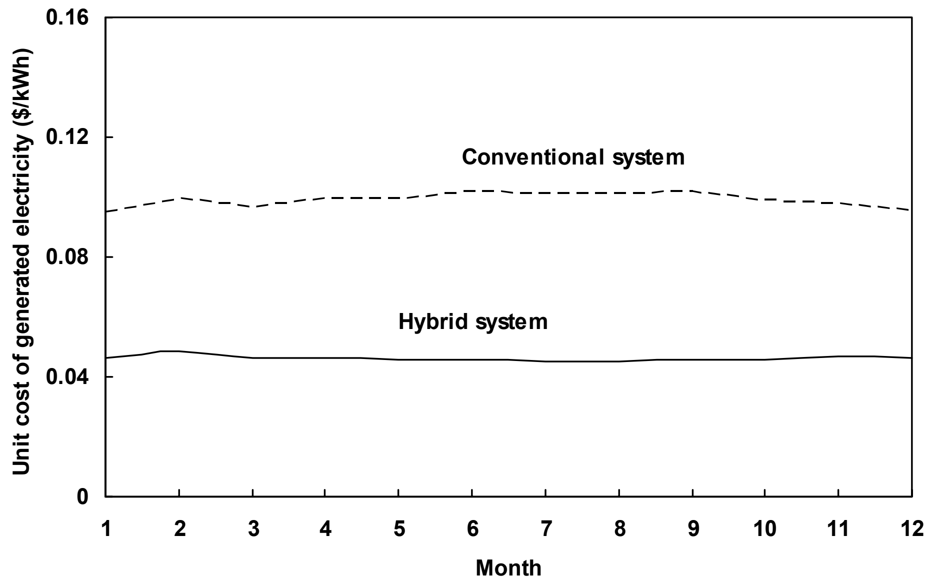

Fig. 5. Unit prices of generated electricity by conventional GT and PV hybrid system.

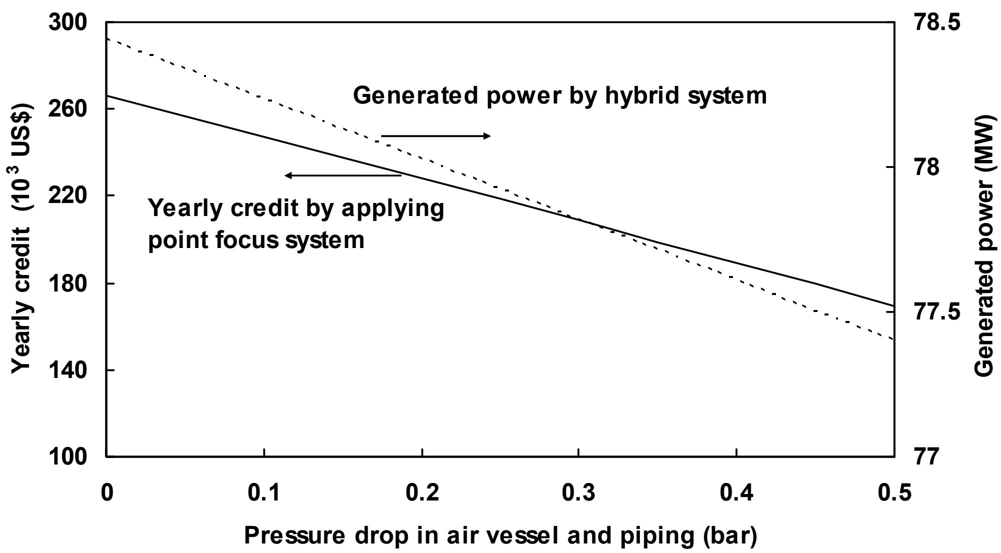

Fig. 6. The effect of pressure drop in the compressed air on the yearly credit and generated power of PV/point focus hybrid system.

The variation of yearly credit and generated power versus the pressure drop in the air storage and piping system is shown in Figure 6. The yearly credit, which represents extra return from surplus electricity, is evaluated from equation. 12. As expected, the change is proportionally linear within the studied conditions. In a real system, pressure ratio (PR) could be increased slightly to cover the predicted pressure drop along the way to expanding turbine. The relative effect of this on motoring energy will be neglected, since there is a free and clean energy source. But as PR increases, the exit temperature, or inlet temperature to later stages of, compressor, hence C_p, increases, whereas mass flow rate, m·, and specific heat ratio decrease [8]. As in conventional gas turbine plants, the generated power from PVGT and CAES is affected directly by variation of air mass flow. In conventional gas turbine engines, the thermal efficiency decreases noticeably at partial load operating conditions. This is considered as a major disadvantage of such plants. However, the proposed PVGT plant would offer excellent characteristics under part load operation; thereby such a new system enjoys economic superiority at part load condition. In addition, it contributes lower levels of gaseous pollutants, especially carbon dioxide, per unit of electricity generated.

To summarize, by integrating the PV, compressed air storage scheme and gas turbine system in one plant, higher energy recovery and power ratios as well as lower heat rates can be achieved. This system is mostly suits dry areas, where there is shortage of water supplies such as the Middle East and North Africa regions, because there is no need for water neither for cooling nor for generation purposes. However, there are some drawbacks such as the complexity due to the integration of different components of the proposed PVGT, huge area required for PV panels and large storage vessel or cavern for compressed air. Thus, higher capital investment is needed compared with other peaking systems.

CONCLUSION

Electricity utilities usually require that peak demand plants be promptly available for operation with simple control and low maintenance costs. At present, conventional gas turbine and pumped hydropower storage plants are widely used for this purpose. However, compressed air storage systems are recognized as being technically feasible and financially attractive for supply-side and load management. This increases the reliability of the power supply and reduces the need for the less cost-efficient peaking units.

In some countries, e.g. Jordan, where the commercial recoverable energy sources are scarce and at the same time enjoying plentiful renewable energy supplies, such as solar energy, the PV technology can be utilised for power generation applications. It is deemed that when PV is used to drive an air compressor during daytime and then the compressed air is used later on, during peak demand, in a gas turbine engine, electricity can be supplied to the grid at reasonably acceptable cost. The proposed new PVGT system will serve as a peaking unit instead of conventional gas turbine plants in arid and semi-arid regions. Preliminary analysis showed that it is possible to generate electricity at a competitive cost as compared to other peaking technologies in the market at present. Moreover, it enjoys higher power ratio of about 2.3%, which means that useful work of this new plant is much higher than that of the conventional system, and produces less gaseous pollutants per unit of electricity generated. But there are some drawbacks such as the complexity of the proposed PVGT, huge area required for PV panels and large storage space, i.e. vessel or cavern, for compressed air as well as relatively high initial capital cost. However, developing such system would ensure that countries within the Middle east region, especially Jordan, would have a cost-effective and environmentally acceptable option for supplying part of its electricity needs from a renewable energy source and at reasonable cost.

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