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Design of an optimized photovoltaic and microturbine hybrid power system for a remote small community: Case study of Palestine

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ABSTRACT

Hybrid systems are defined as systems that utilize more than one energy source to supply a certain load. The implementation of a hybrid system that is based upon Photovoltaic (PV) to supply power to remote and isolated locations is considered a viable option. This is especially true for areas that receive sufficient amounts of annual solar radiation. While analysis of hybrid systems that depend on diesel generators as backup sources can be found in many previous research works, detailed techno economic analysis of hybrid systems that depend on microturbines as backup sources are less addressed. A techno-economic analysis and the design of a complete hybrid system that comprises of Photovoltaic (PV) panels, a battery system, and a microturbine as a backup power source for a remote community is presented in this paper. The investigation of the feasibility of using the microturbines as backup sources in the hybrid systems is one of the purposes of this study. A scenario depending on PV standalone system and other scenario depending on microturbine only were also studied in this paper. The comparison between different scenarios with regards to the cost of energy and pollutant emissions was also conducted. A simulation program was developed to optimize both the sizes of the PV system and the battery bank, and consequently determine the detailed specifications of the different components that make up the hybrid system. The optimization of the PV tilt angle that maximizes the annual energy production was also carried out. The effect of the variation of some parameters on the cost of energy was duly evaluated. Powering a rural community using microturbine alone indicates lower values of cost of energy (COE) production compared to the hybrid system in which a combination of PV panels, battery bank and microturbine has been used. The difference is very small and taking into account the environmental effect of the microturbine surely will make the hybrid system with limited running hours of the microturbine more attractive. Furthermore, as it is obvious from the sensitivity analysis, any reduction in the price of the PV panels or any increase in the natural gas price will make the hybrid system economically and environmentally more attractive.

1. Introduction

Photovoltaic (PV) power sources are ubiquitous as power supply options, especially in remote areas [1–9]. The advantages of using PV panels to generate electricity is the fact that it does not emit pollutants during its operations, its low operating and maintenance costs, long lifetime, and silent operation [10–18].

Hybrid systems are defined as systems that utilize more than one energy source to supply the load. Hybrid systems that include PV panels are widely used to supply various types of loads, especially in remote areas. The low cost of energy production, and the ability to cover load demand under various climatic conditions are usually features that distinguishes hybrid systems from single source systems [19–27].

Palestine receives quite an amount of solar radiation, with high exposure to sunshine hours annually. In the Palestinian territories, the yearly average daily solar radiation on horizontal surface ranges from about 5.5 kW h/m^2 to about 6 kW h/m^2, while the total annual sunshine hours exceeds 3000 h [13]. These values are relatively high, and encourage the use of solar energy for solar water heating or other Photovoltaic (PV) applications. The highest solar radiation is recorded to be in June to August, while the lowest is in December to February.

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Nomenclature

AC_m	additional cost at the beginning of year m ($)
AD	daily autonomy
BTU	British thermal unit
$C_{A\,h}$	storage capacity of the battery (A h)
$CP_{pv\ system\_ini}$	initial PV investment ($)
$C_{W\,h}$	storage capacity of the battery (W h)
Co	future payment ($)
COE	cost of energy ($/kW h)
$CPWF$	cumulative present worth factor
d	discount rate
DOD	depth of discharge of the battery (%)
DR	degradation rate
E_{DL}	total daily load energy (kW h/day)
FF_{MT}	natural gas fuel consumption of the microturbine (m^3/h)
G	solar radiation (W/m^2)
G_{stc}	solar radiation at standard test conditions (G_{stc} = 1000 W/m^2)
i	inflation rate
K_T	temperature coefficient of the maximum power (K_T = -3.7×10^{-3} (1/°C)) for mono and poly crystalline Si
N	year of payment
n	project lifetime
$P_{MT\text{-}out}$	output power of the microturbine (kW)
$P_{R\text{-}PV}$	nominal power of PV cell at reference conditions (W)
$P_{PV\text{-}gen}$	generated power from the PV cell (W)
$P_{PV\text{-}system}$	optimized PV panel size (W)
$P_{pv\ system\_(m)}$	PV system size at year m (kW)
PSH	peak sun hours
$PV_{contribution}$	contribution of the PV system (%)
PWV	equivalent present value ($)
SOC	state of charge of battery
TAC	total annual cost
$TALE$	total annual load energy
$TLCC$	total life cycle cost
T_{amb}	ambient temperature (°C)
T_{cell}	PV cell temperature (°C)
T_{stc}	PV cell temperature at standard test conditions (°C)
η_B	battery efficiency
η_{BDI}	bidirectional inverter efficiency
η_{CR}	charge regulator efficiency

In the Palestinian territories, quite a number of small remote communities are situated far from the grid. The people inhabiting these remote communities use diesel generators to power their homes for a limited period of time, mainly after sunset. Furthermore, about 34.7% of Palestinian households experience interrupted power supply [28]. Electrifying these remote communities and solving the problem of power supply shortage form the priorities of the governmental and nongovernmental organizations based in the Palestinian territories. There are plans to realize this goal, and parts of these projects have been duly implemented. Projects that depend on PV hybrid systems seem to be the most popular amongst these projects. The microturbines can be used as backup sources instead of diesel generators in these PV hybrid systems, which renders the utilization of such hybrid systems more attractive. In comparison to the diesel generator, the microturbine is more reliable, more flexible in terms of fuel, emits less pollutants, requires less maintenance, and is less noisy [29]. Investigation of the feasibility of using microturbines as backup sources in the PV renewable hybrid systems is actually one of the purposes of this study.

Microturbine systems are a relatively new generation of technology. They are classified as small, high speed combustion gas turbines. Their output ranges from 25 kW to 500 kW [30]. Cogeneration forms one of its attractive features, which is defined as its ability to simultaneously generate utilized heat while they are running to generate electricity [31]. A heat exchanger (regenerator) is used for this purpose. Microturbine-generation is currently considered a viable source, and expected to take a significant role in the field of distributed generation technology, due to their relatively low capital costs, small size, and anticipated low operation and maintenance costs [32].

Adopting hybrid systems to provide electricity for different applications is ubiquitous in previous researches [13,24,33–36]. These researches mainly focused on optimization, techno-economic feasibility studies, modeling, environmental issues, and other related research fields. Currently, there are only a few researches that actually analyze the utilization of microturbines in hybrid systems [30,37–40].

Microturbines can be operated as a standalone source to supply base loads. They can also be operated within a hybrid system as a main source, or a standby source. For a distributed generation applications within a grid, they can be operated as a standby source or a peak shaving source.

Ismail et al. [8] used an iterative approach to optimize the sizes of the PV system and the battery bank in the suggested PV/diesel generator hybrid system. Their study was directed toward the tropical climate areas. The same iterative approach was adopted in this paper, where a microturbine was selected as a backup source. As previously mentioned, the feasibility of using the microturbines as backup sources in the hybrid systems will be verified. Furthermore, in this study a detailed techno economic analysis of the suggested hybrid system will be conducted. The sizes of the components making up the hybrid system will be optimized in order to minimize the COE. This includes the size of the PV system (in terms of PV contribution) and the size of the battery bank (in terms of battery autonomy days (AD)). The microturbine power rating will be selected according to the load profile while the sizes of both the bidirectional inverter and the solar charger converter will be selected according to the sizes of the optimized parameters.

In a study involving the Palestinian territories, Daud and Ismail [13] analyzed and designed a hybrid system consisting of a PV, wind turbine, battery bank and diesel generator in order to supply power to a house. The results indicated the superiority of using such hybrid systems, especially in the context of remote areas, compared to conventional sources.

Caisheng et al. [38] studied a hybrid system that consist of a microturbine and wind turbine for standalone applications. An actual residential load profile and real wind data were also taken into account. The simulation results indicated the suitability of adopting this type of hybrid system to supply the residential loads. This hybrid system takes advantages of wind energy, simultaneously minimizing microturbine fuel consumption while maintaining a high level of reliability.

Kalantar and Mousavi [30] suggested a hybrid system consisting of a PV array, wind turbine, microturbine and a storage battery. In this hybrid system, the Microturbine and the storage battery were selected as backup sources. Optimal sizing of the different components that made up the hybrid system was accomplished. The wind turbine and the PV array have the priority to supply the load, while any deficit can be covered by the battery and the