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Optimization of hybrid PV-wind system: Case study Al-Tafilah cement factory, Jordan

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ABSTRACT

Hybrid power systems provide cost-effective utilization of renewable energy but depend on the geographic location due to the variability of solar and wind resources. In this study, a hybrid PV/wind system is proposed for Lafarge cement factory in Al-Tafilah, Jordan. The hybrid system is sized based on maximizing the fraction of demand met by the hybrid system (F_{RES}) with cost of electricity (COE) less than the grid tariff and with 100% renewable energy ratio to meet the renewable energy regulations in Jordan. Furthermore, the effect of the integration of Lithium-Ion bank batteries on the technical and economic feasibility is studied in addition to the effect of carbon social cost on the economic feasibility. The results show that the system with Lithium-Ion batteries is economically more feasible and has higher F_{RES} than the system without energy storage system. The proposed system size is 20.75 MW PV, 26 MW wind systems and 16.8 MWh Lithium-Ion batteries where such system has 62.53% F_{RES}, 0.203 USD/kWh COE, payback period of 3.44 years, net present value of 206.63 M$. In addition, the system will reduce the annual electricity bill of the factory by 21.58 M$ and the CO_2 emissions by 71,373 tons.

Introduction

The growing demand of energy is brought about by increasing populations and industrialization of developed and developing countries. The portfolio of energy supply, however, is still heavily composed of fossil fuels. In Jordan, majority of the energy supply comes from importing heavy oil and natural gas [1,2]. This strains the economy and contributes to carbon dioxide emissions and can be compensated by harnessing solar and wind energy in Jordan. A hybrid plant utilizes multiple forms of energy and delivers a steadier energy generation with higher probability of matching the demand. It can either be coupled with energy storage or without and grid connected or isolated in cases where the national grid is far.

Several studies in the literature investigated the hybridization of different renewable energy systems in different regions and analyzed their technical and economic feasibility. For instance, Boussetta et al. [3] carried a feasibility study of PV-Wind hybrid system to meet the demand of a typical Moroccan city in several regions in Morocco using HOMER software. They concluded that the hybrid system was the optimal solution for all the areas studied except for the areas in the east with low average wind speed. Moreover, Notton et al. [4] made a simulation tool for the operation of PV/wind hybrid system with pumped hydro system where the objective of their study was to reduce the peak load. They used the energy situation- power energy production mixture- of Corsica island as case study and also, simulated several configurations of the hybrid system in order to find the optimal one.

Jordan possesses high potential of renewable energy resources that can significantly contribute in the energy share [2,5,6]. For instance, Jordan has a high solar insolation during the year with 5–7 kWh/m^2 per day [1,2,7,8]. Furthermore, several sites in Jordan has a significant potential of wind energy where the wind speed during the year varies between 3.0 and 7.4 ms^{-1} [1,2] and with power density up to 470 Wm^{-2} [9]. Several studies investigated the economic feasibility of the utilization of wind and solar resources in Jordan. For instance, Al-Salaymeh et al. [10] studied the feasibility of installing PV system in a residential flat in Amman, Jordan. They concluded that the installation of such a system was not feasible due to the high cost of PV systems with minimum payback period of 17 years. Furthermore, Bortolini et al. [11] made a model to investigate the economic and technical feasibility of a grid-tied PV/battery system. The sizing of the system was based on minimizing the LCOE where the best configuration was 350 kW PV and 5.5 Ah battery with LCOE of 0.151 €/kWh. Moreover, Jaber [12] made a reliability and feasibility analysis of grid-tied PV systems in Mediterranean climate, where the optimization was based on minimizing the life cycle cost (LCC) and payback period. They found that the LCC of a PV-grid connected system in Jordan over 30 years was 19,524 USD with

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Nomenclature

A_m	single photovoltaic module area, m^2
C_{ESS}	capital cost of the battery system, USD/kWh
C_i	total capital cost of the renewable energy system, USD
C_L	capital cost of the land, USD
C_{PV}	capital cost of the photovoltaic system, USD/kW
C_{WT}	capital cost of the wind turbine system, USD/kW
CF	annual capacity factor of the hybrid system, %
COE	cost of electricity of the renewable energy system, USD/kWh
COE_C	cost of electricity including social cost of carbon, USD/kWh
COE_o	cost of electricity without including social cost of carbon, USD/kWh
D	electrical demand, kWh
D_{excess}	amount of excess energy from the renewable energy system, kWh
D_{grid}	demand met by the electricity from the grid, kWh
D_{RES}	demand met by the renewable energy system, kWh
DOC	depth of charge of the energy storage system, %
DOD	depth of discharge of the energy storage system, %
DSF	annual demand supply fraction, %
E_{gen}	total yearly energy produced by the renewable energy systems, MWh
E_{PV}	electrical energy generated by the photovoltaic power plant, kWh
$E_{gen,wind}$	electrical energy generated by the wind turbine(s), kWh
E_{stor}^{max}	maximum capacity of the energy storage system, kWh
E_{stor}^{t}	energy stored in the energy storage system at time t, kWh
ER	energy ratio, %
F_{RES}	annual renewable energy fraction, %
FIT	local feed-in tariff, USD/kWh
GT	local grid tariff, USD/kWh
H	number of hours in a year that the RES has totally met the demand
$I_{b,n}$	hourly beam insolation, $Wh\,m^{-2}$
$I_{b,t}$	hourly beam insolation on a tilted surface, $Wh\,m^{-2}$
I_d	diffuse insolation on a horizontal surface, $Wh\,m^{-2}$
$I_{d,t}$	diffuse insolation on a tilted surface, $Wh\,m^{-2}$
I_{Ref}	reference insolation at nominal conditions, $Wh\,m^{-2}$
I_T	global insolation on a tilted surface, $Wh\,m^{-2}$
K	shape parameter of the Weibull distribution of the wind speeds
LT	lifetime of the system, years
	longitude of the location, degree
L_{st}	standard meridian for the local time zone, degree
$LCOE$	levelized cost of electricity of the renewable energy system, USD/kWh
M_t	yearly fixed maintenance cost of the hybrid system, USD
MDF	mean hourly deficit, kWh
N	number of wind turbines
N_m	number of modules in the photovoltaic power plant
$NOCT$	nominal operating photovoltaic cell temperature, °C
NPV	net present value, USD
t	time in a year, hour
P	installed photovoltaic power plant capacity, kW
P_e	average electrical power generated at each hour from the wind turbine, kW
$P_{e,R}$	rated electrical power of the wind turbine, kW
PR	performance ratio of the photovoltaic system, %
PBP	simple payback period, years
R_t	annual net revenues from the system, USD
R_{t1}	annual net revenues for the first year, USD
r	annual discount rate, %
T	total number of hours in the time period
T_{amb}	ambient temperature, °C
T_{PV}	module's temperature, °C
$T_{Ref,NOCT}$	reference module's temperature at nominal conditions, °C
$T_{Ref,STC}$	module's temperature at standard test conditions, °C
T_z	local time zone, h
t_s	solar time, h
t_{std}	local time, h
TCF	turbine capacity factor, %
u_C	cut-in wind speed of the wind turbine, m/s
u_F	cut-out wind speed of the wind turbine, m/s
u_R	rated wind speed of the wind turbine, m/s
u_Z	speed at hub height, m/s
u_1	average wind speed at ground level, m/s
$\bar{u}$	mean wind speed at hub height, m/s
Z	hub height, m
Z_1	height of the ground level, m/s

Acronyms and Abbreviations

COE	cost of electricity
DNI	direct normal irradiation
DSF	demand supply fraction
ESS	energy storage system
GDP	gross domestic product
GHGs	greenhouse gases
HOMER	hybrid optimization model for multiple energy resources
IPP	independent power producer
JEPCO	Jordan electric power company
LCC	life cycle cost
LCOE	levelized cost of electricity
NPV	net present value
PBP	simple payback period
PV	photovoltaic
RES	renewable energy system
SCC	social cost of carbon
TMY	typical metrological year

payback period of 5.88 years.

As hybrid systems enhance the harvesting of renewable energy resources, they became the primary focus of several studies in order to determine its feasibility in Jordan. For instance, Essalaimeh et al. [1] investigated the technical and economic feasibility of installing PV/wind hybrid system for heating and cooling applications in industrial, domestic and commercial sectors in Jordan. The proposed system was 1.2 kW of PV modules and 1 kW wind turbine. They concluded that the system was technically feasible; however, it had long payback period for all the sector. Moreover, Aiad et al. [13] made a model to determine the optimal size of standalone PV/wind hybrid system in Jordan based on minimizing the annual total cost. They concluded that the optimal size was 170.25 kW PV, 258.5 kW wind turbines and 604.66 kWh battery bank, such system had a payback period of 6.93 years and 0.0624 USD/kWh cost of electricity generation.

Mining and manufacturing industries including cement industry are one of the major sources of pollutants either directly by emitting pollutants to the atmosphere as a result of the industrial processes or indirectly by consuming huge amounts of electricity [14–16]. Several studies in the literature analyzed the use of renewable energy system as energy source for mining and manufacturing industries however the studies did not analyze the integration of PV/wind hybrid system with