Energy Conversion and Management 106 (2015) 1024–1038

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

# Economic and environmental bi-objective design of an off-grid photovoltaic–battery–diesel generator hybrid energy system

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ARTICLE INFO

*Article history:*
Received 22 July 2015
Accepted 16 October 2015
Available online 11 November 2015

*Keywords:*
Hybrid energy system
Photovoltaic plant
Battery energy storage
Diesel generator
Levelised cost of electricity
Carbon footprint of electricity

ABSTRACT

Generally, off-grid fossil fuel generators provide energy supply to remote regions. The integration of photovoltaic (PV) plants to battery energy storage (BES) systems potentially increases reliability, the system autonomy and lifetime, reducing the generator working hours and the system environmental impact. PV–BES–Diesel generator hybrid energy systems (HESs) offer technical, economic and environmental benefits compared to traditional off-grid systems. This paper proposes a bi-objective design model for off-grid PV–BES–Diesel generator HESs. The aim is to identify the PV plant rated power, the BES system capacity and the technical configuration able to jointly reduce the levelised cost of the electricity (*LCOE*) and the carbon footprint of energy (*CFOE*). Furthermore, the comparison of the *LCOE* and *CFOE* values of the HES against a traditional diesel generator allows determining the economic and environmental advantages coming from the described system. Despite the proposed model is general and suitable for any installation site and HES configuration, this paper exemplifies its application designing a HES to be installed in a remote village in Yakutsk, Russia. The model takes into account the hourly energy demand, the irradiation and temperature profiles of the installation location calculating the hourly PV plant yield, the battery charge–discharge processes and the required generator energy. Results highlight the technical, economic and environmental feasibility of the system for a context with a medium irradiation level, i.e. ~1400 kW h/(m$^2$ year), and relatively low fuel cost, i.e. 0.7 €/l. For the best economic scenario *LCOE* and *CFOE* reductions are of about 8% and 28%, respectively. Finally, the most effective trade-off between economic and environmental performances leads to a *CFOE* decrease of about 48% and a slight decrease of the economic performances (−2%).

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## 1. Introduction

Worldwide, about 1.3 billion people still have no access to reliable electricity services and rural electrification despite efforts for bringing electrical power to remote regions are encouraged by national and international agencies and work programmes [1]. At the same time, in remote areas, the high investments for grid connections and the parallel cost increase of fossil fuels make hybrid energy systems (HESs) potentially competitive, creating favorable conditions for their diffusion within off-grid applications [2]. HESs integrate renewable energy sources (RESs), e.g. photovoltaic (PV) plant, small wind turbines, etc., fossil fuel based devices, e.g. diesel generators, and energy storage systems to meet the energy demand at any time and everywhere. The interest in HESs increases for both grid connected and off-grid applications. Several scientific contributions face the design of HESs suitable for electrification of rural areas. A recent review is by Akikur et al. [3]. Table 1 classifies recent papers on HESs integrating PV plants, BES units and other RESs and traditional sources. Deep attention is paid on the PV–BES–Diesel generator configurations.

HESs have the purpose to meet the energy demand optimising the operation of each energy source and energy storage system. The identification of the most effective size for each component and of the most proper operation control strategy are crucial for the reduction of the lifetime cost, the environmental impact, the unmet load demand and other key objective functions [41]. Khatib et al. [42] present a review of optimisation techniques for HESs integrating PV plants, while Luna-Rubio et al., Erdinc & Uzunoglu and Upadhyay & Sharma [43–45] review the configurations, control and sizing methodologies for HESs highlighting the technological, economic, socio-political and environmental factors involved within the HES assessment criteria. Globally, the current literature highlights the technical feasibility and the long-term economic sustainability as the most frequently adopted design metrics. The inclusion of the environmental sustainability perspective is less

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http://dx.doi.org/10.1016/j.enconman.2015.10.051
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**Nomenclature**

| | |
|---|---|
| $A_a$ | PV system area, $m^2$ |
| $A_m$ | PV single module area, $m^2$ |
| AH | BES autonomy hours, h |
| $C_{AC}(P_{max})$ | AC distribution unit cost (function of $P_{max}$), €/kW |
| $c_B$ | BES system unitary cost, €/kW h |
| $C_{binv}$ | bidirectional inverter cost, € |
| $C_{cd}$ | control devices cost, € |
| $c_f$ | generator fuel cost, €/l |
| $CFOE$ | carbon footprint of electricity, $kgCO_{2eq}$/kW h |
| $C_{inv}(P_o)$ | PV inverter cost (function of $P_o$), € |
| $C_j$ | total cost for year $j$, € |
| $C_j^B$ | PV–BES system battery replacement cost for year $j$, € |
| $C_j^{binv}$ | PV–BES system bidirectional inverter cost for year $j$, € |
| $C_j^{Gf}$ | diesel generator cost due to fuel consumption for year $j$, € |
| $C_j^{Gm}$ | diesel generator cost due to maintenance activities for year $j$, € |
| $C_j^I$ | PV–BES system inverter cost for year $j$, € |
| $C_j^{OM\&I}$ | PV–BES operation and maintenance cost for year $j$, € |
| $c_m$ | generator hourly maintenance cost, €/h |
| $C_n^C$ | BES system maximum charge rate |
| $C_n^D$ | BES system maximum discharge rate |
| $C_{PV}(P_o)$ | PV module cost including installation cost (function of $P_o$), € |
| $C_0$ | PV–BES system turnkey cost, € |
| $DOD$ | BES system depth of discharge, % |
| $E_{A,h}$ | energy supplied by PV system for hour $h$, kW h |
| $E_{B,h}$ | energy supplied by BES system for hour $h$, kW h |
| $e_G$ | unitary diesel generator system energy cost, €/kW h |
| $E_{G,h}$ | energy supplied by diesel generator for hour $h$, kW h |
| $E_j$ | PV–BES–Diesel generator system energy production for year $j$, kW h |
| $E_L$ | total energy demand for the reference year, kW h |
| $E_{L,a}$ | average hourly energy load, kW h |
| $E_{L,h}$ | energy load for hour $h$, kW h |
| $f_{G,h}(P_{G,h}/P_G^{max})$ | generator specific fuel consumption for hour $h$, kg/kW h |
| $f_G$ | generator average fuel consumption for the reference year, kg/kW h |
| $g$ | inflation rate |
| $H_{I,h}$ | total in-plane irradiation for hour $h$, kW h/$m^2$ |
| $H_{I,r}$ | yearly module reference in-plane irradiation, kW/$m^2$ |
| $I_B$ | BES nominal capacity, A h |
| $I_{B,C}^{lim}$ | BES charge current limit, A |
| $I_{B,D}^{lim}$ | BES discharge current limit, A |
| $K_B$ | BES system nominal capacity, kW h |
| $K_B^{AH=1}$ | BES system hourly storage autonomy, h |
| $K_B^{min}$ | BES system minimum capacity, kW h |
| $K_B^{max}$ | BES system maximum capacity, kW h |
| $l$ | connecting wire length per PV system rated power, m/kWp |
| $LCOE$ | levelised cost of electricity, €/kW h |
| $n$ | PV–BES system lifetime, years |
| $NOCT$ | normal operating cell temperature, °C |
| $OCC$ | opportunity cost of capital |
| $P_{binv}$ | bidirectional inverter nominal power, kW |
| $P_{B,C}^{lim}$ | BES charge power limit, kW |
| $P_{B,D}^{lim}$ | BES discharge power limit, kW |
| $P_D$ | power dissipated through the PV inverter, kW |
| $P_{G,h}$ | generator power for hour $h$, kW |
| $P_G^{max}$ | generator maximum net power, kW |
| $P_m$ | PV single module rated power, kWp |
| $P_{max}$ | maximum user load, kW |
| $P_o$ | PV system nominal power rate, kWp |
| $r_B$ | total number of BES system replacements |
| $r_{binv}$ | total number of bidirectional inverter replacements |
| $r_{inv}$ | total number of PV inverter replacements |
| $SOC_{B,h}$ | BES system state of charge for hour $h$, kW h |
| $T_{a,h}$ | ambient temperature for hour $h$, °C |
| $T_{c,h}$ | PV cell temperature for hour $h$, °C |
| $T_{c,ref}$ | PV cell reference temperature, °C |
| $V_B$ | BES system nominal voltage, V |
| $y_B$ | lead acid battery life-cycle emissions per kW h, $kgCO_{2eq}$/kW h |
| $Y_B(K_B)$ | BES system life-cycle emissions (function of $K_B$), $kgCO_{2eq}$ |
| $Y_{binv}(P_{binv})$ | bidirectional inverters life-cycle emissions (function of $P_{binv}$), $kgCO_{2eq}$ |
| $y_G$ | unitary diesel generator emissions, $kgCO_{2eq}$/kW h |
| $Y_G(P_o, K_B)$ | diesel generator life-cycle emissions (function of $P_o$ and $K_B$), $kgCO_{2eq}$ |
| $y_{inv}$ | PV inverter life-cycle emissions per kW, $kgCO_{2eq}$/kW |
| $Y_{inv}(P_o)$ | PV inverter life-cycle emissions (function of $P_o$), $kgCO_{2eq}$ |
| $y_{PV}$ | PV module life-cycle emissions per $m^2$, $kgCO_{2eq}/m^2$ |
| $Y_{PV}(P_o)$ | PV system life-cycle emissions (function of $P_o$), $kgCO_{2eq}$ |
| $y_{PVstr}$ | PV supporting structures life-cycle emissions per $m^2$, $kgCO_{2eq}/m^2$ |
| $Y_{PVstr}(P_o)$ | PV supporting structures life-cycle emissions (function of $P_o$), $kgCO_{2eq}$ |
| $y_w$ | connecting wire life-cycle emissions per kg, $kgCO_{2eq}$/kg |
| $Y_W(P_o)$ | connecting wires life-cycle emissions (function of $P_o$), $kgCO_{2eq}$ |
| $z_{binv}$ | number of bidirectional inverters |

*Greek letters*

| | |
|---|---|
| $\beta$ | temperature coefficient of solar cell efficiency, 1/°C |
| $\sigma$ | BES system hourly self-discharge rate, % |
| $\rho$ | wire specific weight per wire length, kg/m |
| $\rho_f$ | fuel density, kg/l |
| $\eta_{binv}$ | bidirectional inverter efficiency, % |
| $\eta_{ch}$ | BES system charging efficiency, % |
| $\eta_d$ | PV module annual degradation ratio, % |
| $\eta_{dch}$ | BES system discharging efficiency, % |
| $\eta_e$ | PV electrical efficiency, % |
| $\eta_{inv}$ | PV inverter efficiency, % |
| $\eta_{module}$ | PV module conversion efficiency, % |
| $\eta_{PV,h}$ | PV system overall efficiency for hour $h$, % |
| $\eta_{temp,h}$ | PV system temperature efficiency factor for hour $h$, % |

*Indices*

| | |
|---|---|
| $h$ | index for hours |
| $j$ | index for years |

frequent and, generally, it consists of the ex-post environmental assessment of the previously designed system. Such a methodology is behind, also, some existing commercial tools, e.g. HOMER software [46]. In the system design phase, the adoption of bi-objective approaches, able to find good trade-off solutions between the system economic and environmental sustainability, are rare and no tool, including HOMER software, implements bi-objective approaches. This paper addresses this lack presenting a bi-objective design model for off-grid PV–BES–Diesel generator HESs suitable for applications to a generic installation site. The

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