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Optimum autonomous stand-alone photovoltaic system design on the basis of energy pay-back analysis

J.K. Kaldellis [a,*], D. Zafirakis [a], E. Kondili [b]

[a] Lab of Soft Energy Applications & Environmental Protection, TEI of Piraeus, P.O. Box 41046, Athens 12201, Greece
[b] Optimisation of Production Systems Lab, Mechanical Eng. Dept., TEI of Piraeus, P.O. Box 41046, Athens 12201, Greece

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ABSTRACT

Stand-alone photovoltaic (PV) systems comprise one of the most promising electrification solutions for covering the demand of remote consumers. However, such systems are strongly questioned due to extreme life-cycle (LC) energy requirements. For similar installations to be considered as environmentally sustainable, their LC energy content must be compensated by the respective useful energy production, i.e. their energy pay-back period (EPBP) should be found less than their service period. In this context, an optimum sizing methodology is currently developed, based on the criterion of minimum embodied energy. Various energy autonomous stand-alone PV-lead-acid battery systems are examined and two different cases are investigated; a high solar potential area and a medium solar potential area. By considering that the PV-battery (PV-Bat) system's useful energy production is equal to the remote consumer's electricity consumption, optimum cadmium telluride (CdTe) based systems yield the minimum EPBP (15 years). If achieving to exploit the net PV energy production however, the EPBP is found less than 20 years for all PV types. Finally, the most interesting finding concerns the fact that in all cases examined the contribution of the battery component exceeds 27% of the system LC energy requirements, reflecting the difference between grid-connected and stand-alone configurations.

1. Introduction

According to the Amsterdam Treaty, declaration N° 30 [1], "...*insular regions suffer from structural handicaps linked to their island status, the permanence of which impairs their economic and social development*". Among these handicaps, the insufficient energy structure questions the energy demand satisfaction of local societies. In fact, the electrification of numerous isolated consumers, living in small island regions and rural areas that do not appreciate grid-connection [2], comprises a considerable energy-related problem seeking for solution [3,4]. To support the social and economical development of these regions, local energy demand should be satisfied according to the principles of security of supply, competitiveness and environmental sustainability [5].

To adhere to the above principles and improve the life-quality of several remote consumers, the implementation of autonomous renewable energy based stand-alone systems, able to increase the security of supply levels through distributed generation [6,7], should be considered. Towards this direction, photovoltaic (PV) driven stand-alone systems, such as PV-battery (PV-Bat) configurations, suggest an off-the-shelf energy solution with a broad field of applications and a considerable research background [8,9]. To improve the performance of PV-Bat stand-alone systems, several techno-economic studies have been presented [10–12] that substantially contribute to the satisfaction of both the security of supply and the competitiveness principles. On top of these, the constant growth of the PV market [13,14] and the progress encountered in the fields of PV technology [15] imply further establishment for PV based systems in general, with lower costs [16] and higher efficiencies achieved [14].

On the other hand, PV based configurations are accused of extreme life-cycle (LC) energy requirements. In this context, although one may encounter several research works concerning the energy life-cycle assessment (LCA) of grid-connected systems [17–21], no profound research has been carried out for PV-Bat stand-alone systems. For similar systems to be considered as environmentally sustainable as well, one must ensure that their LC energy content may be compensated by the respective useful energy production. Developing a sizing methodology for the

* Corresponding author. Tel.: +30 210 5381237/5381348; fax: +30 210 5381467.
E-mail address: jkald@teipir.gr (J.K. Kaldellis).
URL: http://www.sealab.gr

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Nomenclature

A_{PV}	Area of the PV module (m^2)
a-Si	Amorphous silicon PV module
BOS	Balance of System
CdTe	Cadmium telluride PV module
CF	Capacity factor of the PV generator
CIS	Copper indium diselenide PV module
DOD	Battery system instantaneous depth of discharge
DOD_L	Battery system maximum depth of discharge
E_{bat}	Energy content of the battery system (kWh)
E_{BOS}	Energy content of the BOS components (kWh)
E_D	Annual electricity consumption of the remote consumer (kWh)
E_{dec}	Energy included in the decommissioning stage (kWh)
E_{loss}	Annual energy losses of the system (kWh)
EPBP	Energy pay-back period of the system (years)
E_{net}	Annual net energy production of the PV generator (kWh)
E_{prod}	Annual electricity production of the PV generator (kWh)
E_{PV}	Energy content of the PV modules (kWh)
E_{rec}	Energy gains through recycling (kWh)
E_{rej}	Annual energy surplus of the system (kWh)
E_{res}	Residual energy of the PV generator (kWh)
E_{tot}	Total energy content of the PV-battery system (kWh)
E_y	Annual useful energy production of the system (kWh)
G	Solar radiation at horizontal plane (W/m^2)
I	Electrical current of the PV module (Amperes)
k_{cc}	Specific energy content coefficient for the charge controller (kWh/kW)
k_{INV}	Specific energy content coefficient for the inverter (kWh/kW)
LC	Life-cycle
Li-ion	Lithium ion batteries
M&O	Maintenance and operation
m_{bat}	Mass of batteries (kg)
mc-Si	Multi-crystalline silicon photovoltaic module
Na–S	Sodium–sulfur batteries
n_{bat}	Service period of batteries (years)
N_{cc}	Rated power of the charge controller (kW)
n_{cc}	Service period of the charge controller (years)
N_D	Power demand of the remote consumer (kW)
Ni–Cd	Nickel–cadmium batteries
N_{INV}	Maximum power of the inverter (kW)
n_{INV}	Service period of the inverter (years)
N_{max}	Peak load demand of the remote consumer (kW)
N_o	Maximum power output of a single PV panel (Watts)
N_{PV}	Maximum power output of the PV array (kW)
n_{sys}	Service period of the installation (years)
PbA	Lead-acid batteries
PV	Photovoltaic
PV-Bat	Photovoltaic-battery
Q	Battery system instantaneous capacity (Ah)
Q^*	Battery system capacity under the zero load rejection criterion (Ah)
Q_{max}	Battery system maximum capacity (Ah)
Q_{min}	Battery system minimum permitted capacity (Ah)
R_{ch}	Charge rate of the charge controller (Amperes)
sc-Si	Single-crystalline silicon PV module
SF	Safety factor
U	Electrical voltage of the PV module (Volts)
U_b	Battery system operation voltage (Volts)
U_{cc}	Charging voltage of the charge controller (Volts)
z	Integer number of PV panels
z_1	Integer number of PV panels in parallel
z_2	Integer number of PV panels in series

Greek letters

β	Tilt angle of the PV panel (degrees)
ΔN	Power surplus of the PV generator (kW)
ε_{BOS}	Specific energy content coefficient of BOS components (kWh/m^2)
ε_{incl}	Gravimetric energy content of batteries (kWh_{incl}/kg)
ε_{out}	Gravimetric energy density of batteries (kWh_{out}/kg)
ε_{PV}	Specific energy content coefficient of PV modules (kWh/m^2)
η_{bat}	Energy efficiency of batteries
η_{PV}	Energy efficiency of PV modules
θ	Ambient temperature (°C)

determination of optimum energy autonomous PV-Bat stand-alone configurations, based on the criterion of minimum embodied energy (i.e. minimum LC energy requirements), is the objective of the present paper.

For this purpose, a fast and reliable numerical code "PHOTOV-III" [11] has been used in order to generate PV-Bat configurations able to guarantee zero load rejections (100% energy autonomy) for a given area and time period examined. The algorithm provides detailed results concerning the energy autonomy and the energy performance of the stand-alone system components, considering also the panel tilt angle, while if using reliable information regarding the system's LC energy requirements, it is possible to determine optimum-size energy autonomous configurations, based on the criterion of minimum embodied energy.

Furthermore, using the energy requirements of optimum configurations and estimating the respective useful energy production, the energy pay-back period (EPBP) may be obtained as well. Various PV-lead-acid (PbA) battery combinations are evaluated and two different case studies are investigated; the first considering an island area of high solar potential (the island of Rhodes) and the second an island area of medium solar potential (the island of Thassos), both islands located at the Aegean Archipelagos region (Greece) where one may encounter several scattered islands with numerous off-grid consumers.

2. Proposed solution

In order to face the urgent electrification problems of numerous remote consumers in areas with considerable solar potential, the following autonomous PV-Bat based installation is proposed (see also Fig. 1). The proposed stand-alone PV-Bat system comprises an array of PV modules connected to a battery, via a battery charge controller that feeds a DC/AC inverter. The battery charge controller switches the PV array off when the battery is fully charged and switches (rejects) the load off before the battery gets completely discharged. Regarding the energy storage system selected (an appropriate battery bank is found to be the most suitable solution given the current technological status [22]), it is essential that the respective capacity should be sufficient in order to store any energy production surplus during sunlight hours, for use during night time or at bad weather conditions. Finally, since most applications are based on alternative current [23], a DC/AC inverter is also required.