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Optimum autonomous photovoltaic solution for the Greek islands on the basis of energy pay-back analysis

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ABSTRACT

Although autonomous photovoltaic (PV) systems are identified as renewable energy technologies able to satisfy the electrification needs of remote consumers, they are strongly accused of their life-cycle energy requirements. To support the specific systems' sustainable character one should be able to ensure minimum period of energy pay-back. In this context, an optimum sizing methodology is developed for stand-alone PV-battery systems in order to obtain configurations of minimum energy content. The proposed methodology is applied to three representative islands across the Greek territory and the results obtained are favourably compared with the up to now – commonly used – diesel-electric generator solution.

1. Introduction

According to the Amsterdam Treaty, declaration No. 30 [1], "… insular regions suffer from structural handicaps linked to their island status, the permanence of which impairs their economic and social development". In this context, one may encounter serious electrification problems in many island areas [2], where the poor infrastructure of local electricity grids does not allow grid-connection for several remote consumers. To face their electrification needs, remote consumers are obliged to rely on the operation of small diesel engines consuming considerable amounts of oil, requiring frequent maintenance and presenting a short period of service.

Acknowledging that the development of remote communities is strongly dependent on their energy status, the principles of security of supply, competitiveness and environmental sustainability [3] should be conserved. To conserve these principles, the support and promotion of renewable energy technologies is necessary [4]. By exploiting indigenous, renewable energy sources (RES), greater levels of energy autonomy may be achieved at a competitive cost, eliminating also the dependence on oil imports and designating environmentally sustainable solutions that may allow the local communities' development (contrariwise to those based on oil-based electricity generation, responsible for extremely high production costs and considerable atmospheric pollution).

More specifically, in areas with high local solar potential, the use of photovoltaic (PV) systems introduces a financially attractive electrification solution [5–7] (even at the micro-level [8]), identified by inconsiderable maintenance requirements, minimum environmental pollution during operation, and continuous technological development [9,10]. In this context, PV stand-alone systems, like PV-battery (PV-Bat) configurations, may satisfy the electricity needs of several remote consumers, even providing 100% energy autonomy. On the other hand, PV-based configurations are strongly accused of extreme life-cycle (LC) energy requirements. In this context, although one may encounter several research works with regards to the energy life-cycle assessment (LCA) of grid-connected systems [11–14], no profound research has been carried out for PV stand-alone systems, including also the energy content of the battery component.

For similar systems to be designated as environmentally sustainable as well, one must ensure minimum period of energy pay-back (EPBP), i.e. establish that their LC energy requirements are fairly compensated by the corresponding energy generation. For this purpose, an optimum sizing methodology for stand-alone PV-Bat systems is currently developed in order to obtain configurations

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Nomenclature

Symbols

A_o	area of a single PV module (m^2)
A_{PV}	total area of the PV modules employed (m^2)
CF	capacity factor of the PV generator
DOD	battery system instantaneous depth of discharge
DOD_L	battery system maximum depth of discharge
E_{bat}	energy content of the battery system (kW h)
E_{BOS}	energy content of the BOS components (kW h)
$E_{BOS(a)}$	energy content of the BOS components excluding electronics (kW h)
$E_{BOS(b)}$	energy content of the electronic BOS components (kW h)
E_D	annual electricity consumption of the remote consumer (kW h)
E_{dec}	energy included in the decommissioning of the PV-Bat system (kW h)
E_{dies}	total energy content of the diesel engine (kW h)
E_{IN}	energy input to the battery bank by the PV energy surplus
E_{inst}	energy included in the installation of the PV-Bat system (kW h)
E_{loss}	annual energy losses of the system (kW h)
$E_{M\&O}$	total energy included in the M&O of the PV-Bat system (kW h)
$E_{M\&O\text{-}annual}$	annual energy included in the M&O of the PV-Bat system (kW h)
$E_{M\&O\text{-}dies}$	annual energy included in the M&O of the diesel engine (kW h)
E_{OUT}	energy output by the battery bank
EPBP	energy pay-back period of the system (years)
E_{prod}	annual electricity production of the PV generator (kW h)
E_{PV}	energy content of the PV modules (kW h)
E_{rec}	energy gains through recycling of the PV-Bat system components (kW h)
E_{res}	residual energy of the PV generator (kW h)
E_{tot}	total energy content of the PV-Bat system (kW h)
E_y	annual useful energy production of the system (kW h)
G	solar radiation at horizontal plane (W/m^2)
I	electrical current of the PV module (A)
k_{cc}	energy content coefficient for the charge controller (kW h/kW)
k_{dies}	energy content coefficient for the diesel engine (kW h/kW)
k_{INV}	energy content coefficient for the inverter (kW h/kW)
m_{bat}	mass of batteries (kg)
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	instantaneous power demand of the remote consumer (kW)
N_d	nominal power of the diesel generator (kW)
n_{dies}	service period of the diesel engine (years)
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 (W)
N_{PV}	instantaneous power output of the PV array (kW)
$N_{PV\text{-}peak}$	peak power output of the PV array (kW)
n_{sys}	service period of the installation (years)
Q	battery system instantaneous capacity (A h)
Q^*	battery system capacity under the zero-load rejection criterion (A h)
Q_{max}	battery system maximum capacity (A h)
Q_{min}	battery system minimum permitted capacity (A h)
R_{ch}	charge rate of the charge controller (A)
SF	safety factor
U	electrical voltage of the PV module (V)
U_b	battery system operation voltage (V)
U_{cc}	charging voltage of the charge controller (V)
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_{cc}	increase of the charge controller nominal power (kW)
$\varepsilon_{BOS(a)}$	energy content coefficient of BOS components exl. electronics (kW h/m^2)
ε_{incl}	gravimetric energy content of batteries (kW h_{incl}/kg)
$\varepsilon_{inst+M\&O}$	installation and M&O energy content coefficient of the PV-Bat system (kW h/m^2)
$\varepsilon_{mod\ fr}$	module frame energy content coefficient (kW h/m^2)
ε_{out}	gravimetric energy density of batteries (kW h_{out}/kg)
ε_{PV}	energy content coefficient of PV modules (kW h/m^2)
ε_{sup}	energy content coefficient of array support, foundations, etc. (kW h/m^2)
η_{bat}	round-trip efficiency of batteries
$\eta_{dies\text{-}el}$	energy efficiency of the diesel engine
η_{PV}	energy efficiency of PV modules
θ	ambient temperature (°C)
ξ	part of M&O energy needs covered by the PV energy surplus

Abbreviations

BOS	balance of system
EPBP	energy pay-back period
LC	life-cycle
LCA	life-cycle assessment
M&O	maintenance and operation
mc-Si	multi-crystalline silicon
PbA	lead-acid
PV	photovoltaic
PV-Bat	photovoltaic-battery
PV-ESS	photovoltaic-energy storage system
RES	renewable energy sources

of minimum energy content that also ensure 100% energy autonomy for the remote consumer each time examined.

Considering the high solar potential of most Greek territories [15] and the poor electricity network infrastructure met in many islands of the country, an integrated study is conducted for three representative island areas, based on long-term solar potential experimental measurements. The corresponding locations suggest high, medium-high and medium solar potential areas, thus allowing for the variation of the local solar potential and the production of different results that are favourably compared with the up to now – commonly used – diesel-electric generator solution.

2. Proposed stand-alone energy solution

In order to face the urgent electrification problems of the numerous remote consumers in areas with remarkable solar