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Optimum sizing of photovoltaic-energy storage systems for autonomous small islands

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ABSTRACT

The electrification of autonomous electrical networks is in most cases described by low quality of electricity available at very high production cost. Furthermore, autonomous electrical networks are subject to strict constraints posing serious limitations on the absorption of RES-based electricity generation. To by-pass these constraints and also secure a more sustainable electricity supply status, the concept of combining photovoltaic power stations and energy storage systems comprises a promising solution for small scaled autonomous electrical networks, increasing the reliability of the local network as well. In this context, the present study is devoted to develop a complete methodology, able to define the dimensions of an autonomous electricity generation system based on the maximum available solar potential exploitation at minimum electricity generation cost. In addition special emphasis is given in order to select the most cost-efficient energy storage configuration available. According to the calculation results obtained, one may clearly state that an optimum sizing combination of a PV generator along with an appropriate energy storage system may significantly contribute on reducing the electricity generation cost in several island electrical systems, providing also abundant and high quality electricity without the environmental and macroeconomic impacts of the oil-based thermal power stations.

1. Introduction

The electrification of autonomous electrical networks, principally undertaken by the use of thermal power stations [1,2] and being responsible for the cause of considerable environmental degradation impacts [3,4], is in most cases described by low quality of electricity available at very high production cost with limited options of control [5], therefore setting some serious barriers to the local community's development [6]. The specific electrical systems are determined by considerably low capacity factors that reveal the frequently intense variations of the local demand profile and the low utilization of the existing power stations [2]. Besides, issues concerning the security of supply arising often (for example Aegean Archipelagos islands), further underline the need for the installation of auxiliary power units or the adaptation of alternative generation methods to be considered.

Furthermore, autonomous electrical networks are subject to additional constraints posed by the operation of diesel and heavy oil units used, as well as the systems' nature itself [7–9]. The impacts of these constraints are illustrated on the maximum penetration limits of renewable energy sources (RES) in the local energy balance [10]. More specifically, the need to protect the operating machines from fast wear and also ensure the dynamic stability of the network requires the establishment of technical minima and dynamic penetration limits, respectively, both posing serious limitations on the absorption of RES-based electricity, primarily qualified by the corresponding sources' variable or even stochastic behavior.

To by-pass these constraints and also secure a more sustainable electricity supply status [11] for small autonomous electrical networks, the concept of combining RES and energy storage systems (ESSs) comprises a promising solution, increasing the reliability of the local network as well [6]. Regarding small scaled autonomous electrical networks, where moderate peak load demand and energy consumption throughout the year should be taken into account, the implementation of combined photovoltaic-energy storage electricity generation systems (PV-ESS) able to meet the local electricity needs, must be appraised [12].

In this context, the present study is devoted to develop a complete methodology, able to define the dimensions of an autonomous electricity generation system based on the maximum available solar potential exploitation at minimum electricity generation cost [12,13]. In addition special emphasis is given to the selection of the most cost-efficient energy storage configuration available [14,15]. Note that an ESS, when sized appropriately [16–18], not only can match a variable solar-based energy

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Nomenclature

Symbols

C_{APS} cost of keeping the existing thermal power stations as a back up station (€)
c_e specific energy capacity cost of the ESS (€/kW h)
C_{ESS} total cost of the energy storage system (in present values) (€)
CF_{grid} capacity factor of the under study electrical network
CF_{PV} capacity factor of the PV installation
c_p specific power cost of the ESS (€/kW)
$C_{PV\text{-}ESS}$ life-cycle total cost of the PV-ESS configuration (in present values) (€)
$c_{PV\text{-}ESS}$ electricity generation cost of the PV-ESS configuration (in present values) (€/kWh)
c_{tps} current electricity production cost of the existing thermal power stations (€/kW h)
c_w specific input energy cost (€/kW h)
d_o energy autonomy of the ESS (h)
DOD instantaneous depth of discharge of the ESS
DOD_L maximum permitted depth of discharge of the ESS
e mean annual escalation rate of the produced electricity price
EC cost of input energy utilized to charge the energy storage system (€)
E_{dir} energy demand covered directly by the existing power stations (kW h)
E_{ESS} energy storage capacity of the ESS (kW h)
E_h average hourly load of the electrical network under study per annum (kW)
E_{PV} energy production of the PV installation (kW h)
E_{PVdir} energy yield of the PV installation absorbed directly by the local network (kW h)
E_{PVmin} minimum annual energy production of the PV installation (kW h)
E_{PVrej} rejected amounts of energy produced by the PV installation (kW h)
E_{stor} energy demand covered directly by the ESS (kW h)
E_{stor1} energy contribution of the ESS during daytime (kW h)
E_{t1} energy demand of the local electricity network during sunlight periods (kW h)
E_{t2} energy demand of the local electricity network during sunlight absence (kW h)
E_{tot} energy demand of the local electricity network (kW h)
f balance of the plant coefficient
$FC_{PV\text{-}ESS}$ fixed *M* and *O* cost of the entire PV-ESS configuration (€)
FC_{ESS} fixed *M* and *O* cost of the ESS (€)
FC_{PV} fixed *M* and *O* cost of the PV installation (€)
G solar irradiance (k Wh/m^2)
g_{ESS} mean annual change of cost for the ESS
g_j mean annual change of cost for the ESS major parts to be replaced
g_k mean annual change of cost for the PV installation's major parts to be replaced
g_{PV} mean annual increase of cost for the PV installation
I electrical current of the PV module
i capital cost of the local market
IC_{ESS} initial cost of the ESS (€)
IC_{PV} initial cost of the PV installation (€)
$IC_{PV\text{-}ESS}$ initial cost of the entire PV-ESS configuration (€)
j_{max} number of time-steps for the under study period
jth major components of the ESS
k_o major parts to be replaced during the system's service period for the PV installation
k_s major parts to be replaced during the system's service period for the ESS
kth major components of the PV installation
l_j times of replacement for the ESS major parts being replaced (integer number)
l_k replacement times for the PV installation's major parts (integer number)
m_{ESS} ratio of annual *M* and *O* cost to the total initial investment for the ESS
m_{PV} ratio of annual *M* and *O* cost to the total initial investment for the PV installation
n years of operation for the PV-ESS configuration (years)
N_{APS} rated power of the existing autonomous power stations (kW)
N_{ESS} nominal output power of the ESS (kW)
n_{ESS} service period of the ESS (years)
N_{in} maximum input power of the ESS (kW)
n_j lifetime of the ESS major parts to be replaced
n_k lifetime of the PV installation's major parts to be replaced
N_{p1} peak load demand of the local electricity network during the noon (kW)
N_{p2} peak load demand of the local electricity network during the evening (kW)
$N_{p\text{-grid}}$ peak load demand of the local electricity network (kW)
N_{PV} rated power of the PV installation (kW)
$n_{PV\text{-}ESS}$ lifetime of the entire PV-ESS configuration (years)
Pr specific price of the PV installation (€/kW)
r_j replacement cost coefficient for the ESS major parts to be replaced
r_k replacement cost coefficient for the PV installation's major parts to be replaced
s ratio of energy demand during sunlight to energy demand during sunlight absence
SF safety factor considering the electrical network and the PV installation
U electrical voltage of the PV module
$VC_{PV\text{-}ESS}$ variable maintenance cost of the entire PV-ESS installation (€)
w mean annual escalation rate of the input energy price
x_3 ratio of the PV installation contribution during daytime

Greek symbols

γ ratio of state subsidy to the total investment cost
Δt duration of each time step
δE energy contribution of the local APS (kW h)
δE_1 energy contribution of the local APS during daytime (kW h)
ε energy demand ratio covered directly by the ESS
ζ peak load demand ratio covered by the ESS
η_{ESS} energy transformation efficiency of the ESS (round-trip)
η_p power efficiency of the ESS
θ ambient temperature (°C)
λ ratio of the maximum ESS input power to the corresponding rated output power
ξ ratio of the ESS contribution during daytime
ρ_j mean annual technological progress change for the PV installation's major parts
ρ_k mean annual change of technological progress for the ESS major components
Y_n residual value of the PV (€)

Abbreviations

APS autonomous power station
ESS energy storage system
FC fuel cells
M and *O* maintenance and operation