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Wind powered pumped-hydro storage systems for remote islands: A complete sensitivity analysis based on economic perspectives

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HIGHLIGHTS

- ▶ Electricity production in most remote islands is based on expensive oil imports.
- ▶ The contribution of wind power is restricted due to electrical grid limitations.
- ▶ The techno-economic behavior of a wind-based pumped hydro storage system is examined.
- ▶ Guaranteed energy amounts at peak load demand hours are provided by the proposed system.
- ▶ Based on the optimum solution renewables may cover 25% of the island's energy needs.

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ABSTRACT

The electrification of the non-interconnected Greek islands is mainly based on Autonomous Power Stations (APSs) that are characterized by considerably high electricity production cost, whilst, in several cases, problems related with power shortage are encountered. At the same time, the contribution of wind energy is significantly restricted due to electrical grid limitations imposed to "secure" the stability of the local network and thus resulting in significant rejected wind energy amounts. On the basis of sensitivity analysis, the present study evaluates the techno-economic viability of a system that incorporates the simultaneous operation of existing and new wind farms (WFs) with pumped storage and hydro turbines, which are able to provide the electrical grid of a remote island with guaranteed energy amounts during the peak load demand hours on a daily basis. The performance of the system is simulated during a selected time period for various system configurations and an attempt is made to localize the optimum solution by calculating various financial indices. Emphasis is given on the conduction of an extensive sensitivity analysis considering three main variables (i.e. produced energy selling price, the percentage of state subsidization and the price of the wind energy surplus bought from the already existing WFs) taking also into account several constraints of the national legislation. Based on the most economically viable (payback period quite less than 10 years) configuration derived (24 MW WFs, 15 MW water pumping system, 13.5 MW hydro turbines), the contribution of renewable energy increases by almost 15% (in absolute terms) compared to current conditions, reaching about 25% of the island's energy consumption pattern. The proposed analysis may be equally well applied to every remote island possessing remarkable wind potential and appropriate topography.

1. Introduction

The energy production of the non-interconnected Greek islands is mainly based on Autonomous Power Stations (APSs) which consume conventional fossil fuels, while the contribution of Renewable Energy Sources (RESs) (mainly wind) accounts for only 9% of the total electricity generation in these regions. Specifically, in 2008, the total electricity production was approximately 6250 GW h from which only 580 GW h derived from renewables [1]. The Greek Public Power Corporation (PPC), being the exclusive supplier and practically the sole producer of the energy deriving from fossil fuels combustion, faces considerable electrification problems related to power shortage, seasonal load demand variations, weak transmission electricity networks and outdated thermal power units. Moreover, the electrification of the islands is closely associated with very high energy production costs that may in many cases exceed – during peak hours – the 200 €/MW h, much depending though on oil prices since the fuel cost sharing accounts for more than 50% [2,3].

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Nomenclature

C	investment expenses (€)
c_f	fuel cost (€/MW h)
c_{HT}	price of the electricity sold to the local utility network (produced by the hydro turbines) (€/MW h)
c_{PPC}	price of the energy bought by the island electrical network's operator (€/MW h)
c_{WF}	price of the electricity sold to the local utility network (produced by the wind farms) (€/MW h)
c^*_{WF}	price of the electricity bought from the existing wind farms (€/MW h)
e	price escalation rate (hydro turbines energy production) (%)
e_1	price escalation rate (for energy absorbed by the local grid) (%)
E_C	energy input cost (€)
E_a	wind energy absorption by the local grid of the already existing WFs before the installation of the proposed project (MW h)
E'_a	wind energy absorption by the local grid of the already existing WFs after the installation of the proposed project (MW h)
E_{HT}	energy absorbed by the local grid (produced by the hydro turbines) (MW h)
E_P	total absorbed energy for charging the storage system (wind farms + local grid) (MW h)
EPC_{HT}	energy production specific cost of the proposed configuration (€)
EPC_{PPC}	peak energy production specific cost of the thermal power units (€)
E_{PPC}	absorbed energy by the local grid for charging the storage system (MW h)
$E_{rejected}$	rejected annual wind energy amounts by the local grid (MW h)
E^*_{WF}	absorbed energy by the existing wind farms for charging the storage system (MW h)
E_{WF}	energy absorbed by the local grid (produced by the new wind farms) (MW h)
E''_{WF_j}	total annual wind energy (from both the existing and new wind farms under investigation) absorbed for charging the storage system (MW h)
F_C	fixed maintenance & operation cost (€)
f_e	escalation factor used to appraise the time value of money (hydro turbines energy production)
f_{W_1}	escalation factor used to appraise the time value of money (new wind farms energy production)
G	revenues of the investment (€)
g_m	*M & O* cost inflation rate (%)
i	cost of money (%)
IC_{EM}	initial cost of the electromechanical equipment (€)
IC_{CE}	initial cost of the civil engineering work (€)
IC_o	initial cost of the entire installation (€)
IC_{others}	initial other costs (€)
IC_{TB}	tubes' initial cost (€)
m_1	fraction of the electromechanical equipment cost (%)
m_2	fraction of the civil engineering work cost (%)
n	project's lifetime
n^*	investment's payback period
N_{HT}	rated power of hydro turbines (MW)
N_{WF}	rated power of wind farm (MW)
N_{WP}	rated power of water pumps (MW)
P_R	public rates (€)
$P_{r_{HT}}$	specific cost of hydro turbines and generators (€/MW)
$P_{r_{st}}$	specific cost of water reservoirs construction (€/m^3)
$P_{r_{WF}}$	specific cost of wind turbine installation (€/MW)
$P_{r_{WP}}$	specific cost of the water pumps (€/MW)
R	investment incomes (€)
T	taxes paid by the system's owner enterprise (€)
V_C	variable maintenance & operation cost (€)
v_r	percentage of the wind power surplus that is going to be absorbed from each wind farm for charging the storage system (%)
V_{st}	total volume of water reservoirs (m^3)
V_{up}	volume of the upper reservoir (m^3)
V_{upmin}	minimum volume of the upper reservoir (m^3)
w	price escalation rate (existing wind turbines energy production) (%)
w_1	price escalation rate (new wind turbines energy production) (%)
Y	residual value of the investment at the end of the project's lifetime (€)

Greek letters

α	private capital (%)
β	loan (%)
γ	state subsidy (%)
ξ_1	percentage of the gross annual investment incomes which is directly transferred to the local municipality as public rates (%)
φ	tax coefficient (%)

Other symbols

j	annual values
o	constant values at the investment starting point
$\sim$	present values

Abbreviations

APSs	Autonomous Power Stations
HT	hydro turbine
M & O	maintenance & operation
NPV	Net Present Value
npv	NPV divided by the private capital invested
PPC	Public Power Corporation
RESs	Renewable Energy Sources
WF	wind farm
WPHS	wind-based pumped-hydro storage

On the other hand, despite the high wind potential encountered in many Greek island regions, the wind energy contribution to the electrification of these areas is significantly restricted mainly due to existing technical barriers, which protect the autonomous electrical grids from possible instability problems [4,5]. The intermittent nature of the wind in combination with remarkable fluctuations of daily and seasonal electrical load demand have lead to strict wind energy penetration limits [6,7], thus making it difficult to achieve higher than 15% wind energy contribution in autonomous electrical networks [8,9]. To overcome the intermittency and uncertainty of wind and to establish wind power as a more reliable technology able to remarkably contribute to the electrification of remote areas, a combination of hydro and wind power generation by means of pumped-storage [10–12] under economically viable terms seems to be the most advantageous solution [13–16].

In this context, the techno-economic performance of a wind-based pumped-hydro storage (WPHS) system [17,18], capable to exploit rejected wind energy amounts from both existing and