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# Optimum sizing of wind-pumped-storage hybrid power stations in island systems

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ABSTRACT

Pumped storage is generally viewed as the most promising technology to increase renewable energy source (RES) penetration levels in power systems and particularly in small autonomous island grids. Combined wind and pumped-storage “virtual power plants”, called hybrid power stations (HPS), constitute a realistic and feasible option to achieve high penetrations, provided that their components are properly sized. In this paper, the optimum sizing is investigated for a pumped storage HPS operating in an island system. The analysis addresses the sizing of the main HPS components (hydro turbines, pumps, wind farm, reservoirs), adopting either the investor’s perspective, where the objective is to maximize the return on the HPS investment, or a system perspective, where the optimization target is the maximization of RES penetration, along with maintaining the lowest possible generation cost in the system. Genetic Algorithms (GAs) are applied for the optimization and a real isolated island power system is used as a study case. The adopted operating policy and pricing principles, which critically affect the optimal sizing of an HPS project, are based on the existing regulatory framework for storage stations in Greek islands.



## 1. Introduction

High generating costs, dependence on oil products and environmental considerations have been a powerful driver for the increasing exploitation of the renewable energy potential during the last decades [1,2], wind energy being the most significant so far. Energy storage is considered as the most effective means to significantly increase wind penetration levels in power systems, [3,4], particularly in the case of isolated island grids where technical limitations are imposed by conventional generating units and the limited size of the systems, [5–9]. Pumped storage is currently the most mature centralized storage technology, particularly suited for facilitating large scale RES integration in medium and large power systems, due to its high power and energy capacity, [3,4,10]. A favorable and realistic way to introduce pumped storage in island systems is based on the concept of HPSs, which are virtual power plants comprising WFs and storage facilities, operating in a coordinated manner, [11–17].

To maximize the benefits and fully exploit the potential arising from the introduction of storage, proper sizing of the HPS components is necessary. So far, the optimum sizing of pumped storage facilities in similar applications has been the subject of relatively few publications, [18–23]. In Ref. [18], besides defining a suitable operating policy, the sizing of an HPS in Canary islands is investigated for optimum exploitation of the available hydraulic and wind potential, without adverse effects on system reliability. In Ref. [19], the size of pumps and reservoirs is optimized for maximum exploitation of the wind potential of an island, using a linear programming method. In Refs. [20,21], the design of a pumped hydro-storage system for the recovery of the energy rejected by WFs in the non-interconnected Greek islands Lesvos and Crete, respectively, is analyzed in detail with the aid of dedicated optimization tools based on evolution algorithms. The recovery of rejected wind energy by pumped storage has been examined also for the interconnected electric power system of Greece, [22], where the optimum pumped storage scheme is investigated to combine an existing large hydroelectric power plant with a new pumping station unit. In Ref. [23] the sizing of a combined wind-hydro pumped storage system is optimized for the case of the isolated power system of Karpathos-Kasos, where the operation of this system is based on the condition of guaranteed energy supply to the local grid on a daily basis during the peak load demand hours. Also, the developing of seawater pumped storage systems for co-operation with the existing WFs has been investigated in

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**Nomenclature**

*Abbreviations*

| | |
|---|---|
| APS | autonomous power station |
| DG | distributed generation |
| FiT | feed-in-tariff |
| GA | genetic algorithm |
| HFO | heavy fuel oil |
| HPS | hybrid power station |
| HTS | hydro turbine station |
| IRR | internal rate of return |
| LCOE | levelized cost of energy |
| LFO | light fuel oil |
| MOEA | multi-objective evolutionary algorithms |
| O&M | operation and maintenance |
| RES | renewable energy source |
| VOC | variable operating cost |
| WF | wind farm |

*Symbols*

| | |
|---|---|
| AC | avoided cost due to the integration of the HPS |
| $CAE_{APS}$ | annual capital amortization expenses of the APS |
| $CAE_{HPS}$ | annual capital amortization expenses of the HPS |
| $CAE_{RES}$ | annual capital amortization expenses of all RES stations, besides the HPS |
| $C_{HPS}$ | energy payments to the HPS |
| $C_{RES}$ | remuneration to all RES stations, except the HPS |
| CRF | capital recovery factor |
| $E_D$ | load declaration submitted by the HPS for the next day |
| $E_G$ | guaranteed energy demanded by the Island System Operator from the HPS over the next 24 h period |
| $E_H$ | stored hydraulic energy of HPS |
| $E_{HH}$ | produced energy by the HTS of the HPS |
| $E_{HP}$ | absorbed energy by the HPS pumps |
| $E_{HW}$ | produced energy by the WF of the HPS |
| $E_L$ | annual load energy demand (excluding the HPS pumping load) |
| $E_O$ | energy offer submitted by the HPS for the next day |
| $E_R$ | produced energy by all RES stations, besides the HPS |
| $FC_{APS}$ | fixed annual operating cost of the APS |
| $F(x)$ | objective function vector |
| $F_t$ | net income for year $t$ (after taxes and loan amortization) |
| $i$ | annual discount rate |
| $IC_{con}$ | HPS interconnection cost |
| $IC_H$ | investment cost of HPS hydro turbine station |
| $IC_{other}$ | other investment costs of HPS |
| $IC_P$ | investment cost of HPS pump station |
| $IC_R$ | investment cost of HPS reservoirs |
| $IC_W$ | investment cost of HPS wind farm |
| $IC_{0,eq}$ | investment equity |
| $IC_{0,tot}$ | total investment cost of a power station |
| $N$ | investment (economic) lifetime |
| $OMC_{HPS}$ | O&M cost of the HPS |
| $OMC_{RES}$ | O&M cost of all RES stations, except the HPS |
| $P_{conv}$ | conventional generation capacity |
| $P^A_{con,min}$ | minimum conventional generation requirements on an annual basis |
| $P^j_{conv,min}$ | minimum daily conventional generation requirements |
| $P_G$ | guaranteed power demanded by the Island System Operator from the HPS over the next 24 h period |
| $P_H$ | installed hydro turbine capacity |
| $P_{HG}$ | HPS guaranteed power |
| $P_{L,max}$ | peak annual load demand of the island |
| $P_P$ | installed pump station capacity |
| $P_W$ | installed WF capacity |
| $P^*$ | Pareto optimal set |
| $PF^*$ | Pareto front |
| $RES_{Pen}$ | annual RES energy penetration level |
| $VC_{APS}$ | variable cost of the APS |
| $V_R$ | capacity of water reservoirs |
| $x$ | optimization variable vector |

Ref. [24] for the islands of Crete and Kasos, including feasibility study as well as precise positioning of the system components and selection of the main equipment.

In all cases, the sizing of the HPS components depends on the operating strategy assumed, the investment cost and the applicable energy/power tariffs, as well as on the adopted optimization targets. In this paper, the optimization is performed for the specific operating policy described in Refs. [11–13], that is based on an existing regulatory framework, as applied in Greek islands, according to which the storage facilities are perceived as the tool for introducing significant additional wind capacity in saturated island systems, rather than as a means for increasing the energy yield of WFs already existing on the islands.

Two alternative perspectives are adopted in the paper regarding the optimization targets: a) The investor's perspective, where the objective is to maximize the return of the HPS investment. It is the realistic view in today's electricity markets, where investors act as independent entities seeking maximum profit. b) The system perspective, setting as optimization targets the increase of RES penetration, along with maintaining the generation cost of the overall system as low as possible. The second perspective constitutes a multi-objective optimization problem and it resembles the traditional approach followed in generation system planning, seeking to minimize the overall generation cost of the system. It would be the perspective adopted in a hypothetical single-owner situation (similar to the vertically integrated monopolies of the past), but this might also be a perspective of interest to the planning authorities, seeking to maximize RES penetration at the lowest possible LCOE, when addressing the development of the generation system. GAs are applied as the basic optimization tool, [25–27], along with Pareto optimality concepts, [28,29], employing a real island power system as a study case.

The paper is organized as follows. In Section 2, a short description of the examined island system is given, an outline of the adopted operating policy and pricing principles are presented and a short description of the model used for the annual simulation of the system is presented. The optimization problem is described in Section 3, where the optimization variables are presented and the objective functions are defined for each one of the alternative perspectives. The optimization algorithms used are described in Section 4. Results for the study case system and several different scenarios are presented and discussed in Section 5, while the main conclusions of this work are summarized in Section 6. Data used in the analysis are provided in Appendix A, the philosophy of HPS capacity remuneration is clarified in Appendix B, while basics of the Pareto optimality theory, also employed in this paper, are included in Appendix C.