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Application of a generic superstructure-based formulation to the design of wind-pumped-storage hybrid systems on remote islands

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ABSTRACT

This paper aims to present a mathematical model for the design of a hybrid power system (HPS) to support a remote island with 100 thousand citizens. The goal is to reduce diesel fuel consumption by adequate expansion of wind power supply. Pumped hydroelectric storage (PHS) is used in the HPS to buffer the impact of intermittent behavior of wind energy. A superstructure is proposed for HPS design, considering all possible capital decisions (e.g. the number of wind turbines) and hourly-basis operational variables (such as the amount of surplus electricity in storage and its discharge). The HPS design problem can then be formulated as a mixed-integer linear program (MILP) based on the proposed superstructure. For a given total share of wind power, the optimal mix of diesel-based and wind power supplies as well as the required capacity of PHS are determined using a four-step optimization approach, involving minimizing (i) the consumption of diesel fuel, (ii) the number of wind turbines, (iii) the size of the upper water reservoir, and (iv) the charge/discharge rates of the PHS system. In this sequential optimization, the objective value obtained in a previous step is added as an additional constraint to the next step. The proposed HPS design model is applied to a real case study of the remote K Island on the other side of Taiwan Strait using hourly-basis, year-round historical data. Inclusion of other renewable energy sources, such as photovoltaic cells and biomass-fired power plants, as well as economic perspectives will be considered in future work.

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1. Introduction

Electricity brings great convenience to human life. However, there is a massive population living in remote areas or villages where as many as 1.3 billion people are beyond the reach of the public power grid [1]. Formerly, it is common for those people to use diesel-fired power plants for electricity generation. However, the price of diesel fuel has increased by more than four times in the last decade. On the other hand, recent advances in sustainable energy technologies such as wind turbines and photovoltaic (PV) cells has improved the competitiveness of renewable energy (RE). The use of available RE sources gives alternative options for electricity generation, especially for remote areas without connection to the public grid.

The K Island under study has 100 thousand citizens, and is located on the other side of the strait, about 280 km away from Taiwan. The annual electricity demand on the K Island is approximately 246 GW h, which is supplied mainly by a diesel-fired power plant due to its isolation from the main public grid. Due to the increasing diesel fuel price, the hybrid power system (HPS) is considered a viable option for reducing the dependence on diesel fuel for electricity generation on the remote K Island. An HPS makes use of two or more power sources including renewables (e.g. wind turbines and PV systems) and conventional energy sources (such as diesel generators) as backup [2]. Comparisons of different grid-independent hybrid power generation systems can be found in the review paper of Panapakidis et al. [3]. Due to the intermittent nature of most RE sources, it is commonly suggested to incorporate energy storage, in the form of batteries [4], fuel cells [5], or pumped hydroelectric storage (PHS) [6], in the HPS to cope with uncertainties in RE supplies. Díaz-González et al. [7] reviewed various energy storage technologies for wind power applications. It is also emphasized that energy storage techniques are crucial for increased penetration of renewables in islanded systems [8]. Arun et al. [9] proposed using the design space approach to minimize the size of photovoltaic-battery systems under different reliability levels where the uncertainty associated with solar insolation was taken into account. The design space method was also used by

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Nomenclature

Indices and sets
$i \in \mathcal{I}$ power sources
$n \in \mathcal{N}$ days in a year
$t \in \mathcal{T}_n$ time intervals at particular day n
$t \in \mathcal{T}_n^{p} \subseteq \mathcal{T}_n$ peak time intervals at day n

Parameters
$\overline{F}_n$ maximum outlet flow rate of PHS system (kW)
g gravitational acceleration (9.81 m/s^2)
H elevating head (m)
P^{off} the lowest monthly average power demand during off-peak times (kW)
$\overline{P}_i$ basic available size of the power source i (kW)
P_{int}^{gen} recorded power rating from existent wind turbine within time interval t of day n (kW)
P_i^{inst} installed capacities of the wind turbine (kW)
P_{nt}^{dm} power rating of demand within time interval t of day n (kW)
$\overline{F}^{out}$ maximum outlet flow rate of PHS system (kW h)
$\underline{F}^{out}$ minimum outlet flow rate of PHS system (kW h)
η^{in} overall efficiency of motor-pump of PHS system
η^{out} overall efficiency of the turbine-generator of PHS system
Δ_t length of time interval t (h)
ρ density of water (1000 kg/m^3)
σ hourly evaporation and leakage losses of PHS system (1/h)
α_1 a ratio to restrict maximal allowable real-time supply from wind turbines
α_2 a ratio to restrict maximal allowable overall supply from wind turbines

Continuous variables
e^{cap} installed capacity of UR (kW h)
f_{nt}^{aux} an auxiliary variable to obtain f_n^{out} (m^3/h)
f_{nt}^{in} water flow rate pumped into PHS within time interval t of day n (m^3/h)
f_n^{out} water flow rate flow out of the UR at day n (m^3/h)
f_{nt}^{out} water flow rate flow out of the UR within time interval t of day n (m^3/h)
h^{in} power charged into PHS system (kW)
h^{out} power discharged from PHS system (kW)
h_{nt}^{dm} hydraulic power provided from pumped hydro storage to demand within time interval t of day n (kW)
h_{nt}^{ex} excess hydraulic power from pumped hydro storage within time interval t of day n (kW)
h_{nt}^{in} power charged into PHS system within time interval t of day n (kW)
h_{nt}^{out} power discharged from PHS system within time interval t of day n (kW)
p_{int} rated power generation from source i within time interval t of day n (kW)
p_{int}^{dm} power from source i to demand within time interval t of day n (kW)
p_{int}^{hy} power from source i to PHS system within time interval t of day n (kW)
p_{int}^{ex} excess power from source i within time interval t of day n (kW)
q^{cap} volume of UR (m^3)
q_{nt} accumulated water in UR within time interval t of day n (m^3)
$Y_{nt}^{out} \in \{-1, 0, 1\}$ for water gate action of PHS within time interval t of day n

Integer variables
m_i number of basic available size of wind turbine facilities

Binary variables
$z_{nt}^{in} \in \{0, 1\}$ for occurrence of power charged into PHS within time interval t of day n
$z_{nt}^{out} \in \{0, 1\}$ for occurrence of power generated from PHS within time interval t of day n
$z_{nt}^{+} \in \{0, 1\}$ for turning on water gate of PHS within time interval t of day n
$z_{nt}^{-} \in \{0, 1\}$ for turning off water gate of PHS within time interval t of day n

Sreeraj et al. [10] to estimate the electricity cost of a HPS of a remote area.

In recent years, both categories of process integration techniques, namely pinch analysis and mathematical optimization, have been extended for HPS design and optimization problems. For targeting the maximum RE availabilities of a typical HPS, Wan Alwi et al. [11] proposed using the power pinch analysis (PoPA) technique for optimal power allocation in an HPS; the technique was then extended by Mohammad Rozali et al. [12,13] to consider possible power losses during conversion, transfer and storage. Chen et al. [14,15] presented transshipment model-based linear programming (LP) and mixed-integer linear programming (MILP) formulations for designing off-grid hybrid power networks with minimum electricity outsourced from the public grid. Furthermore, Chen and coworkers solved the HPS design problem with power loss considerations using a generic superstructure-based LP model [16] and another simple transshipment model-based LP formulation [17]. Both categories of techniques have recently been well developed, being able to take into account power losses during the conversion, transfer and storage of power in HPS design with constant efficiency parameters, and therefore the minimum outsourced electricity supply as well as the minimum battery capacity required can be determined [13,16]. However, both of these studies are limited to relatively simple HPSs. For a practical, large-scale HPS on an isolated remote island, there are additional constraints on operation to be considered, such as the maximum share of RE. Therefore, a more comprehensive approach is needed for further application of HPS design methods.

Among the various energy storage alternatives, PHS appears to be the most popular for its capability of short-term and long-term storage. Padrón et al. [18] presented a case study with the use of a pumped storage system to increase the penetration level of RE in an isolated power system. Katsaprakakis et al. [19] also reported a novel application of a wind powered pumped storage system. Kapsali et al. [20] analyzed the economic perspectives of wind powered PHS systems for remote islands. Margeta et al. [21] investigated a photovoltaic-hydro energy system for sustainable energy production. Recently, a mathematical model and the operation principle are developed to assess the technical feasibility of the hybrid solar-wind system with PHS on a remote island [22]. In addition, Ma et al. [23] presented a novel techno-economic opti-

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