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Integrated operation of renewable energy sources and water resources

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ABSTRACT

To respond to the global climate change, Taiwan has announced an ambitious target for the development of renewable energy, which is characterized by solar power 20 GW and wind power 4.2 GW by 2025, but the intermittency of renewable energy sources might have serious impacts on the existing power grid. Not only the energy system but also water resources will be impacted by the global climate change. In Taiwan, the strength of rainfall increases but the frequency of rain decreases; this factor combined with a disadvantageous topography to store rainfall worsens the water-shortage issues. As a solution of the aforementioned issues related to the renewable energy sources and water resources concurrently, an integrated system and its operating model for renewable energy sources and water resources are proposed according to which hydropower, pumped-storage hydropower, solar power, wind power, desalination plants and the conjunctive use of water between two reservoirs are considered. A mathematical model is established to describe how the system works under various input data. The results show that, with a retrofit of existing old units and the addition of 102-MW new units, the hydropower unit of the proposed system can eliminate a requirement of 853-MW gas-fired power plants during peak loading in the reference case; the cost, US$45 million per year, of power generation can be saved. With 1099-MW pumped-storage hydropower units added, the proposed system and its operating model further enhance the peak-loading support; relative to a battery-storage system in the reference case, the cost of energy storage can save US$166 million per year. As for the desalination plants in the proposed system, the cost of producing water still exceeds that of the planned reservoir in the reference case because of its greater cost of operation. On considering the total benefit from the water and energy sector, the extra expense, US$41 million per year, for desalination can, however, be readily compensated; the proposed system can save more, US$171 million per year, than the reference case.

1. Introduction

In a context of a global climate change, renewable energy has been greatly promoted all over the world. In 2016, the total installed capacity of the existing power generating system in Taiwan was 49.9 GW; the total installed capacity of wind power and solar power was less than 2 GW. The plan announced by the Taiwan government to develop renewable energy by 2025 is ambitious; the capacity setting of solar power is 20 GW, wind power 4.2 GW, hydropower 2.15 GW, biomass 0.813 GW and geothermal 0.2 GW; their total power generation will share 20% of the power demand in Taiwan by 2025. With their rapid deployment, the unit costs of renewable energy sources (RES) are decreasing, but the issues to overcome the intermittent nature of RES are becoming serious. When the penetration of RES attains 5–10%, the impact of the intermittency on the power grid is no more ignorable [1]. The global climate change affects not only energy policy but also water issues. Taking Taiwan as an example, the topography of Taiwan is precipitous; the rivers are short and rapid; the sedimentation of existing reservoirs is serious because of violent typhoons every year. With the increased strength and the decreased frequency of rainfall resulting from the global climate change, the reserve of water becomes increasingly difficult. This consequence worsens the problem of water shortage in recent years despite the annual rainfall being sufficient for the annual demand in Taiwan.

Power generation is invariably accompanied by water consumption, which might occur during the fabrication of equipment or during power generation. Several researchers have contributed their efforts to the amount and cost of water consumption for power generation [2]. In this work, this issue is not addressed, but the problems of supply and demand of water and power are explored. Without considering hydropower, the issues of supply and demand for the energy and water sectors were formerly solved independently, but, as these two sectors can be combined to extract benefit greater than working them independently, there is increasing research on trying to capture the nexus

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Nomenclature

AE_{BS}	annual power generation of a battery system, kWh/year
AE_{PSH}	annual power generation of PSH, kWh/year
AP_{hydro}	annual power generation during the period of peak-power demand by additional hydro units, kWh/year
AS_{hydro}	required support of annual power generation from existing NGCC plants because of operation of hydropower units of ISRWR, kWh/year
AS_{PSH}	required support for annual power generation from existing natural gas combined-cycle power plants because of the operation of PSH of ISRWR, kWh/year
AW_r	annual production of water in the new reservoir, Mm^3/year
$Cost_{IS}$	additional annual cost required by ISRWR for water supply, power storage and power generating services, US$
$Cost_R$	additional annual cost required by the Case Ref. for water supply, power storage and power generating services, US$
C_{BES}	installed capacity of battery energy-storage system, MW
C_{des}	desalination unit capacity, Mm^3/h (million cubic meter per hour)
$C_{hydro,\ i}$	proposed hydro-turbine capacity of unit i, MW
$C_{hydro,\ PSH}$	proposed pumped-storage hydroelectric capacity, MW
$E_{balance}$	power demand after subtracting wind and solar power, MW
E_d	power demand, MW
PSH	pumped-storage hydroelectricity
Q_{des}	water supplied by the desalination plant, Mm^3/h
$Q_{dome,i}$	domestic water supply by reservoir i, Mm^3/h
Q_{eco}	outflow for ecological consideration, Mm^3/h
$Q_{flush,i}$	flushing flow rate from reservoir i, Mm^3/h
$Q_{hydro,i}$	water through hydro-turbine of unit i, Mm^3/h
$Q_{hydro,max}$	maximal flow for hydropower under a specified water level, Mm^3/h
$Q_{hydro,PSH}$	hydro flow rate of pumped-storage hydroelectricity, Mm^3/h
Q_{pump}	pumping flow rate of pumped-storage hydroelectricity, Mm^3/h
$Q_{agri,i}$	the agricultural water supply by reservoir i, Mm^3/h
$Q_{balance}$	balance of inflow and outflow in Shigang reservoir, Mm^3/h
Q_d	water demand, Mm^3/h
$Q_{pump,max}$	maximum rate of pumping flow of pumped-storage hydroelectricity, Mm^3/h
$Q_{tri,i}$	inflow from tributaries upstream of reservoir i, Mm^3/h
Q_{union}	positive for water support from Shigang to Liyutan, and negative for water support from Liyutan to Shigang, Mm^3/h
R_{CC}	electricity price of existing natural gas combined-cycle power plants, US$/kWh
RES	renewable energy resources
$S_{r,i}$	water amount of reservoir i, Mm^3
$E_{d,hihi}$	upper limit of power demand, MW
$E_{hydro,PSH}$	hydro power generated by pumped-storage hydroelectricity, MW
EL_{lolo}	below this limit of water level, hydropower is prohibited, m
$EL_{r,i}$	water level of reservoir i, m
E_{pump}	pumping power of pumped-storage hydroelectricity, MW
EL_{hi}	above this elevation, hydropower is fully operated, m
EL_{hihi}	above this elevation, flushing is required, m
$ISRWR$	integrated system for renewable energy sources and water resources
LC_{BS}	levelized cost of power production for a battery storage system, US$/kWh
LC_{des}	levelized cost of water production for desalination plant, US$/$m^3$
LC_{hydro}	levelized cost of power production for an additional hydropower unit, US$/kWh
LC_{PSH}	levelized cost of power production for PSH, US$/kWh
LC_r	levelized cost of water production for new reservoir, US $/$m^3$
Mm^3	million cubic meter
$S_{r,hihi}$	amount of water in Techi reservoir for water level at EL_{hihi}, Mm^3
$S_{virtual}$	virtual amount of water storage of Liyutan reservoir, Mm^3
T_{PSH}	duration of pumping, h
T_{BES}	duration of BES discharge, h
t	time, h
X_{PSH}	output ratio of PSH, (0–1, dimensionless)
X_{hydro}	output ratio of hydropower units, (0–1, dimensionless)
ϕ_{des}	specific energy consumption of desalination, kWh m^{-3}
$\phi_{hydro,i}$	proposed hydro-turbine efficiency at design point for unit i, %
$\phi_{hydro,PSH}$	proposed hydro-turbine efficiency at design point for PSH, %
ϕ_{pump}	proposed pumping efficiency of PSH,%

Subscripts

i	1 through 8 denote units or reservoirs for Techi, Chin-Shan, Guguan, Tianlun, Maan, Shigang, Liyutan and Tien-Hwa-Hu reservoir, respectively
j	the upstream reservoir of reservoir i, $j = i - 1$
k	reservoir in which hydropower unit i discharges water
land	land-based wind power
off	offshore wind power
solar	solar power

between the RES and water resources.

The most typical way to integrate the water resources and RES is through pumped-storage hydro (PSH), according to which the RES become stored within an upper reservoir of PHS during periods of excess supply and released for subsequent use in periods of high demand. There are more than 20 GW and 7.4 GW of PSH at the planning stage in USA and EU, respectively [3]. Many researchers are exploring how to use PSH to harness the excess wind power in an economic manner. For example, Anagnostopoulos et al. [4] used a simulation model to evaluate the critical factors for a PSH to recover the wind energy rejection in the power system of Greece; the results showed that the installed capacity of wind power, the available capacity of the reservoir and the operating strategies of the hydro-turbine are the key factors. Tuohy et al. [5] performed an economic analysis on replacing some gas-fired power plants with PSH and a high penetration of wind power in Ireland. Chen et al. [6] proposed a mathematical model to maximize the utilization of RES and to minimize the use of diesel generators in an island with the help of PSH. Portero et al. [7] demonstrated a combination of seawater PSH with wind power, which might decrease the cost of power generation. Ma et al. [8] studied how to determine an optimal combination among wind power, solar power and PSH.

In a remote area or island or Middle-east country, some researchers are trying to integrate renewable energy with desalination techniques to solve the scarcity of power and water. Georgiou et al. [9] used multi-criteria analyses to evaluate the economic and environmental issues of a small-scale desalination plant with power sources in varied combinations. Mentis et al. [10] tried to supply the entire water demand of arid islands in the South Aegean Sea with desalination plants; they