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Economic justification of concentrating solar power in high renewable energy penetrated power systems

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HIGHLIGHTS

- We propose a novel method to perform the economic justification of CSP.
- CSP benefits include providing both renewable energy and operational flexibility.
- The break-even investment cost of CSP plants is analysed.
- Economic justifications of CSP in two provincial power systems in China are studied.
- CSP is much more competitive in power systems under high renewable penetrations.

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ABSTRACT

Concentrating solar power (CSP) plants are able to provide both renewable energy and operational flexibility at the same time due to its thermal energy storage (TES). It is ideal generation to power systems lacking in flexibility to accommodate variable renewable energy (VRE) generation such as wind power and photovoltaics. However, its investment cost currently is too high to justify its benefit in terms of providing renewable energy only. In this paper we evaluate the economic benefit of CSP in high renewable energy penetrated power systems from two aspects: generating renewable energy and providing operational flexibility to help accommodating VRE. In order to keep the same renewable energy penetration level during evaluation, we compare the economic costs between the system with a high share of VRE and another in which some part of the VRE generation is replaced by CSP generation. The generation cost of a power system is analyzed through chronological operation simulation over a whole year. The benefit of CSP is quantified into two parts: (1) energy benefit—the saving investment of substituted VRE generation and (2) flexibility benefit—the reduction in operating cost due to substituting VRE with CSP. The break-even investment cost of CSP is further discussed. The methodology is tested on a modified IEEE RTS-79 system. The economic justifications of CSP are demonstrated in two practical provincial power systems with high penetration of renewable energy in northwestern China, Qinghai and Gansu, where the former province has massive inflexible thermal power plants but later one has high share of flexible hydro power. The results suggest that the CSP is more beneficial in Gansu system than in Qinghai. The levelized benefit of CSP, including both energy benefit and flexibility benefit, is about 0.177–0.191 $/kWh in Qinghai and about 0.238–0.300 $/kWh in Gansu, when replacing 5–20% VRE generation with CSP generation.

1. Introduction

Increasing share of renewable energy sources (RES) in the generation mix of power systems creates additional variability and uncertainty that must be properly accommodated for economic and reliable system operations. Currently, wind power and photovoltaic (PV) generation capacities are rising quickly. By the end of 2016, the global installed capacity reached 487 GW for wind and 302 GW for PV [1]. In places of Demark, Ireland, Texas of U.S. and northwestern provinces in China, the penetration of RES has already reached a quite high level (serving more than 20% of total electricity demand) [2]. Wind power and PV generations are named variable renewable energy (VRE) because of the variability and uncertainty in their power outputs that are driven by prevailing weather conditions. The increasing integration of VRE may

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Nomenclature

Indices and sets

t time index
i thermal unit index
Ω_T set of time periods for one day from t1 to t24
Ω_{Thm} set of thermal units
Γ set of time periods for the whole dispatching simulation time scope
f subscript for thermal units that can start and stop daily
c subscript for thermal units that cannot start and stop daily
h subscript for hydro power units
w subscript for VRE units
s subscript for concentrating solar power plants

Parameters and constants

[1] column vector which has unity elements
C_x column vector of variable operational cost of unit type x, $x \in \{f,c,h,w,s\}$
C_d column vector of load shedding cost
C_{wd} column vector of VRE curtailment cost
V_f column vector of start-stop costs of thermal units belonging to type f
C_{ave} column vector of estimated average generating cost of power system
ΔP_{down}, ΔP_{up} column vector of maximum and minimum ramp rates of generating units
$P_{\max}$, $P_{\min}$ column vector of maximum and minimum outputs of generating units
$P_w^{t,fore}$ column vector of forecasted VRE generation at time slot t
$P_s^{t,fore}$ column vector of available solar thermal power at time slot t
, $\eta^{PB}\eta^{TES}$ coefficients of power block efficiency and TES efficiency in CSP plants
D^t column vector of nodal loads at time slot t
r_d^t, r_u^t system up and down reserve requirements at time slot t
A_{ngx} units and nodes incidence matrix of unit type x, $x \in \{f,c,h,w,s\}$
W generation shifted distribution factor matrix
$F_{\max}$ column vector of transmission line capacity
$C_i(*)$ generation cost function of thermal unit i
$C_i^{fuel}(*)$ fuel cost function of thermal unit i
$C_i^{ramp}(*)$ ramp cost function of thermal unit i
$C_i^{su}(*)$ start-stop cost function of thermal unit i
a_i, b_i, c_i, d_t coefficients of the cost function of thermal unit i
α renewable energy generation penetration level
β generation share of CSP in renewables
FCR annual fixed charged ratio

Variable

S_f^t column vector of start-stop cost of generating units belonging to type f
P_x^t column vector of dispatched output of unit type x, $x \in \{f,c,h,w,s\}$
P_{wd}^t column vector of VRE curtailed at time slot t
I_f^t column vector of on/off status of thermal units with type f at time slot t
I_c column vector of on/off status of thermal units belonging to type c
I_s^t column vector of on/off status of CSP plants at time slot t
E_s^t column vector of state of charge of TES in CSP plants at time slot t
$P_s^{cha,t}$ column vector of charging output of TES in CSP plants at time slot t
$P_s^{dis,t}$ column vector of discharging output of TES in CSP plants at time slot t
D_d^t column vector of nodal load shedding at time slot t
P_i^t output of thermal unit i at time slot t in the scenario without substituting VRE with CSP generation
$P_i^{t'}$ output of thermal unit i at time slot t in the scenario with substituting VRE with CSP generation
G_{VRE} investment capacity of VRE in the scenario without substituting VRE with CSP
G'_{VRE} investment capacity of VRE in the scenario with substituting VRE with CSP
G'_{CSP} investment capacity of CSP in the scenario with substituting VRE with CSP
CSR_{CSP} capacity substitute rate of CSP plants
LEB_{CSP} levelized energy benefit of CSP generation
LFB_{CSP} levelized flexibility benefit of CSP generation
LOB_{CSP} levelized overall benefit of CSP generation
EB_{CSP} overall energy benefits of CSP investment
FB_{CSP} overall flexibility benefits of CSP investment
ROI_{CSP} return of Investment for CSP plants
BEC_{CSP} break-even cost of CSP plants

lead to additional requirements for operational reserves and ramping capacities, and thus reduce the operational benefit of renewable energy [3].

Power system operational flexibility denotes the ability of controllable generation units in changing their outputs to meet the variances of electricity loads, uncontrollable generation outputs and grid conditions. Since VRE generation is generally not dispatchable, net load is often used to evaluate the system operational flexibility requirement through treating VRE generation as negative load. Generally, the operational flexibility is provided by conventional fossil-fueled controllable generations, and the integration of VRE increases the requirement of operational flexibility.

Compared with wind and PV, concentrating solar power (CSP) plants are able to generate dispatchable renewable energy electricity [4,5]. Specifically, a CSP plant controls mirrors with tracking system to capture the direct normal irradiation (DNI) of sunlight which is then converted into thermal energy for utilization in a steam turbine to produce electricity. CSP plants allow for the incorporation of cost-efficient thermal energy storage (TES) to store the absorbed solar thermal energy for later use. This makes it possible for CSP to provide renewable energy and operational flexibility at the same time. The introduction of TES brings multiple benefits to CSP plants from several perspectives. First, since CSP plants can shift electricity generation using TES, it is capable of providing dispatchable generation and operational flexibility in power systems. Second, TES can remarkably increase the capacity factor of CSP through equipping larger solar collection fields, since surplus solar thermal energy can be stored in TES. Furthermore, TES systems in CSP plants are currently less costly (with capital costs around 20–70 $/kWh) than battery energy storage systems (with capital cost above $150/kWh) [6]. Compared with conventional thermal plants, CSP is generally regarded to be a semi-dispatchable technique due to the limit of absorbed solar energy [7].

Although the CSP development encounters some obstacles, such as much high capital cost and considerable land/water requirement, the advantages of CSP and the increasing need of renewable energy still attract widespread interests in CSP development [8]. E.g. CSP has considerable water requirements only when using wet-cooling, dry-cooling technique which significantly reduces the water demand is