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Economic optimization of operations for hybrid energy systems under variable markets

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HIGHLIGHTS

- Propose method for maximizing system economics based on renewable and market info.
- Develop computational platform for performing operations optimization.
- Develop control to manage prediction error and storage to avoid energy imbalance.
- Illustrate advantages of optimizer by comparing flexible and constant operations.
- Perform sensitivity analysis under market variability and prediction error.

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ABSTRACT

Hybrid energy systems (HES) have been proposed to be an important element to enable increasing penetration of clean energy. This paper proposes a methodology for operations optimization to maximize their economic value based on predicted renewable generation and market information. A multi-environment computational platform for performing such operations optimization is also developed. To compensate for prediction error, a control strategy is accordingly designed to operate a standby energy storage element (ESE) to avoid energy imbalance within HES. The proposed operations optimizer allows systematic control of energy conversion for maximal economic value. Simulation results of two specific HES configurations illustrate the proposed methodology and computational capability. Economic advantages of such operations optimizer and associated flexible operations are demonstrated by comparing the economic performance of flexible operations with that of constant operations. Sensitivity analysis with respect to market variability and prediction error are also performed.

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1. Introduction

1.1. Background and motivation

Hybrid energy systems (HES) under flexible operations and variable energy generations/utilizations have been proposed to be an important element to enable higher penetration of clean energy generation, e.g., renewable and nuclear options, [1–9]. HES typically integrate multiple energy inputs (e.g., nuclear and renewable energy) and multiple energy outputs (e.g., electricity, gasoline, and fresh water) using complementary energy conversion processes. By enabling more than one option for energy utilization, HES configurations can change their electricity generation or consumption within a short time whenever requested.

Prior works have been focused on dynamic modeling and simulation of diverse unit operations, together with their integration, control, and dynamic property characterization [5–8]. These results suggest that, from a technical point of view, HES can be operated under flexible operations schedules to accommodate the variability introduced from renewable generation, modern loads (such as electric vehicles), and markets. Such flexibility allows HES to participate in several wholesale markets, including markets for electrical energy, feedstock, and alternative energy outputs. Previous technical evaluation of HES has also shown that HES meet the requirements to bid into wholesale ancillary service (AS) market [5], to support the stability of the electric grid. A high-level diagram of a general HES considered here is shown in Fig. 1, where HES take energy inputs from Controllable Energy Resources (CER) such as baseload generation (e.g., nuclear station), Variable Energy Resources (VER) such as wind farm, and Energy Storage Elements (ESE) such as electrical battery. HES typically include one or more Alternative Production Plants (APP) besides a Power Cycle

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Nomenclature

α_{ahg}	capital cost per unit of installed capacity of AHG
α_{app}	capital cost per unit of installed capacity of APP
α_{ese}	capital cost per unit of installed capacity of ESE
α_{phg}	capital cost per unit of installed capacity of PHG
α_{ren}	capital cost per unit of installed capacity of REN
β_{co_2}	taxation rate over CO_2
β_{f_ahg}	fraction between $O\&M_{f\_ahg}$ and C_{ahg}
β_{f_app}	fraction between $O\&M_{f\_app}$ and C_{app}
β_{f_ese}	fraction between $O\&M_{f\_ese}$ and C_{ese}
β_{f_phg}	fraction between $O\&M_{f\_phg}$ and C_{phg}
β_{f_ren}	fraction between $O\&M_{f\_ren}$ and C_{ren}
$\beta_{v\_ahg,n}$	price of the nth feedstock by AHG
$\beta_{v\_app,n}$	price of the nth feedstock by APP
γ_{co_2}	coefficient for computing GHG emission
π_{app}	price of alternative product
$\pi_{da,as}$	price of ancillary service in DAM
$\pi_{da,e}$	price of electrical energy in DAM
π_{rt}	price of electrical energy in RTM
$\rho_{da,k}$	depreciation and amortization rate for year k
σ	tax rate
$\tilde{}$	prediction of corresponding variables
B_1, B_2, B_3	feasibility conditions
C_{ahg}	auxiliary heat generation capital cost
C_{app}	alternative production plant capital cost
C_{cap}	total capital cost
C_{ese}	energy storage system capital cost
$C_{ghg,k}$	cost for GHG emission for year k
$C_{O\&M,k}$	operations and maintenance cost for year k
C_{phg}	primary heat generation capital cost
C_{ren}	renewable energy generation capital cost
$CAPEX_k$	capital expense for year k
DA_k	depreciation and amortization for year k
$FCFF_{R,k}$	year-k real discounted free cash flow to firm
i	inflation rate
M_{app}	production rate of alternative product
M_{co_2}	combined CO_2 emission
$M_{v\_ahg,n}$	consuming rate of the nth feedstock by AHG
$M_{v\_app,n}$	consuming rate of the nth feedstock by APP
$O\&M$	operations and maintenance
$O\&M_f$	fixed operations and maintenance cost
$O\&M_v$	variable operations and maintenance cost
$O\&M_{f\_ahg}$	fixed O&M cost of AHG
$O\&M_{f\_app}$	fixed O&M cost of APP
$O\&M_{f\_ese}$	fixed O&M cost of ESE
$O\&M_{f\_phg}$	fixed O&M cost of PHG
$O\&M_{f\_ren}$	fixed O&M cost of REN
$O\&M_{v\_ahg}$	variable O&M cost of AHG
$O\&M_{v\_app}$	variable O&M cost of APP
P_{app}	power generated by PHG and consumed by APP
P^L_{app}	minimum power consumed by APP
P^U_{app}	maximum power consumed by APP
p_{as}	probability of reserved capacity to be called for
$P_{da,as}, P^U_{da,as}$	AS sold in DAM and its upper limit
$P_{da,e}$	amount of electrical energy sold in DAM
$P_{da,rt}, P^U_{da,rt}$	power held for RTM and its upper limit
P_{phg}	power generated by PHG
P_{ren}	power generated by REN
P_{rt}	amount of electrical energy sold in RTM
R_k	revenue for year k
r_R	discount rate
R_{app}	revenue from sale of alternative product
$R_{da,as}$	revenue from sale of ancillary service in DAM
$R_{da,e}$	revenue from sale of electrical energy in DAM
R_{rt}	revenue from sale of electrical energy in RTM
T_{pb}	payback period
$\mathcal{N}_{ahg}$	installed capacity of AHG
$\mathcal{N}_{app}$	installed capacity of APP
$\mathcal{N}_{ese,1}$	installed capacity of smoothing ESE
$\mathcal{N}_{ese,2}$	installed capacity of standby ESE
$\mathcal{N}_{phg}$	installed capacity of PHG
$\mathcal{N}_{ren}$	installed capacity of REN
AHG	auxiliary heat generation
APP	alternative production plants
AS	ancillary service
CER	controllable energy resources
CHP	combined heat and power
CM	commodity market
DAM, DAO	day-ahead market, day-ahead optimizer
DB	database
ESE	energy storage systems
FM	feedstock market
FMI	functional mockup interface
FOM	figure of merit
ForM	forward market
GHG	greenhouse gas
GPP	gasoline production plant
HES	hybrid energy systems
HES_FEL	HES with flexible electrical load
HES_FTL	HES with flexible thermal load
HRES	hybrid renewable energy systems
IRR	internal rate of return
MW, MW h	megawatt and megawatt-hour
NG	natural gas
NPV	net present value
PC	power cycle
PHG	primary heat generation
PM	power market
PV	photovoltaics
REN	renewable energy input
RODP	reverse osmosis desalination plant
RTM	real-time market
RTO	real-time optimizer
SM	spot market
VER	variable energy resources
WACC	weighted average cost of capital

(PC) for electricity generation. These APP allow the repurposing of energy (in form of thermal energy and/or electrical energy) for non-electricity commodity production. HES interrelate with feedstock market FM_i for procurement of feedstock material f_i, with power market PM for the sale of electricity and ancillary service, and with commodity market CM_j for the sale of commodity c_j (alternative energy output). Furthermore, each market (FM, PM and CM) in turn includes several forward and spot markets.

Hence the objective of this paper is to develop a generic methodology and computational platform for computing operations schedule among HES constituents for optimal economic performance. As shown in Fig. 2, such operations optimizer collects predicted information on VER generation and markets (denoted with dash lines), and updates the operations of the given HES through low-level controllers. Since HES participate in ancillary service market, controllers are also subject to grid system operator commands in case that reserved capacity is called upon. Note that since prediction error can cause energy imbalance within HES, an ESE is utilized to ensure energy balance at all time, as shown in Fig. 1.