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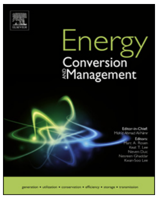

A multi-objective optimization and multi-criteria evaluation integrated framework for distributed energy system optimal planning

Rui Jing[a], Xingyi Zhu[a], Zhiyi Zhu[b], Wei Wang[a], Chao Meng[a], Nilay Shah[c], Ning Li[a], Yingru Zhao[a,*]

[a] College of Energy, Xiamen University, Xiamen, China
[b] East & West Region, CLP Power Hong Kong Limited, Hong Kong Special Administrative Region
[c] Department of Chemical Engineering, Imperial College London, London, UK

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ABSTRACT

This study proposes an integrated framework for planning distributed energy system with addressing the multi-objective optimization and multi-criteria evaluation issues simultaneously. The framework can be decomposed into two stages. At the optimization stage, the system design and dispatch are optimized considering multiple objectives by Ɛ-constraint method. Three decision making approaches are applied to identify the Pareto optimal solution. At the evaluation stage, a combined Analytic Hierarchy Process and Gray Relation Analysis method is proposed to evaluate and rank various optimal solutions when different objectives and cases are considered. Two stages of work are integrated by introducing the baseline conditions. As an illustrative example, an optimal planning model for a solar-assisted Solid Oxide Fuel Cell distributed energy system is proposed by Mixed Integer Non-linear Programming approach firstly. Then, the system is applied to different cases considering two types of buildings located in three climate zones. The obtained optimal solutions are further evaluated by the proposed multi-criteria evaluation method. Therefore, the overall optimal system design and dispatch strategy, as well as the best demonstration site can be identified comprehensively considering multiple objectives. In general, the results have verified the effectiveness of the proposed framework.

1. Introduction

The problem of fossil fuel depletion is becoming increasingly crucial nowadays due to the growth of world's energy demand. In order to meet the energy demand as well as to limit the production of carbon dioxide, the development of new technologies for energy consumption management and the change from conventional fuel to sustainable fuel are stringent necessity. Recently, attention has been drawn to develop cleaner alternative fuels from renewable resources for the combined cooling, heating and power (CCHP) systems [1]. CCHP is an efficient alternative for building energy supply [2], which draws world-wide attention gradually. Several technologies can be the prime movers of CCHP system including internal combustion engines, gas turbines, Stirling engines, micro turbines and fuel cells [3]. Among all available CCHP prime movers, fuel cells are considered as one of the most promising technologies due to the high energy efficiency and low emissions [4]. Among various types of fuel cells, the Solid Oxide Fuel Cells (SOFCs) are perfect prime movers for the CCHP systems due to intrinsically better electrical efficiency (as high as 60%) and significantly lower pollutant emissions, which makes them a promising alternative for building energy supply [5].

1.1. Literature review

Previous studies have been conducted on modelling the high-level system design and dispatch of CCHP systems to study their feasibility and optimal technique combination. Each study has slightly a different research focus and solves an aspect of the problem from different perspectives.

The MILP (Mixed Integer Linear Programming) and MINLP (Mixed Integer Non-Linear Programming) modelling approaches have been proved by previous studies to be effective ways to solve the design and dispatch optimization problem. Nojavan et al. [6] Proposed an optimal scheduling model for CHP based energy hub considering economic and environmental objectives' trade-offs. Two solving methods, i.e., ε-constraint and max–min fuzzy satisfying, were employed to solve and select the trade-off solution. Zhao et al. [7] proposed a two-stage dispatch optimization model which can tackle the real-time load variation. Jin et al. [8] proposed an MILP model which considers the demand response, meanwhile, day-ahead and adaptive dispatch strategies have been applied to reduce the uncertainty. Ma et al. [9] constructed a MILP model for optimal dispatch of multiple energy systems at micro energy

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[*] Corresponding author.
E-mail address: yrzhao@xmu.edu.cn (Y. Zhao).

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Nomenclature

Abbreviations

ATC	annual total cost
ACE	annual carbon emission
AHP	Analytic Hierarchy Process
ASHP	air source heat pump
BL	baseload
CCHP	combined cooling heating and power
CRF	capital recovery factor
CES	carbon emission saving
GRA	Gray Relation Analysis
HEX	heat exchanger
IEA	International Energy Agency
LINMAP	Linear Programming Technique for Multidimensional Analysis of Preference
LCOE	levelized cost of energy
MINLP	Mixed Integer Non-linear Programming
MILP	Mixed Integer Linear Programming
OPEX	operating expenditures
OPEXS	operating expenditure saving
OEF	on-site energy fraction
OEM	on-site energy matchness
OEP	on-site energy performance
SOFC	solid oxide fuel cell
SRI	solar radiation index
TOPSIS	Technique for Order Preference by Similarity to an Ideal Solution

Symbols

AM	air mass
A	area (m^2)
C	cost ($)
CAP	installed capacity (kW)
d	deviation index
E	electrical power (kW)
ED_{i+}	distance to ideal point
ED_{i-}	distance to non-ideal point
f	part load efficiency function
f_{ij}^{norm}	location of each optimal point
f_j^{ideal}	location of ideal point
$f_j^{\mathrm{n-\,ideal}}$	location of non-ideal point
h	hour
PL	part load ratio
Y_i	relative distance
Q	thermal energy (kW)
T	temperature (°C)

Greek symbols

ω	heat-to-power ratio
η	efficiency
α	charge/discharge status
δ	import/export status
β	on/off status
φ	start limit variable
∂	emission factor
μ	energy conversion factor

Subscripts/superscript

ac	absorption chiller
b	boiler
cap	capital cost
cool	cooling energy
chr	heat storage charge
dis	heat storage discharge
ec	electrical chiller
ex	electricity export
fc	solid oxide fuel cell
h	hour
heat	heating energy
hp	heat pump
im	electricity import
LHV	low heating value
limit	installed capacity limit
maint	maintenance cost
NG	natural gas
n	project life
pv	photovoltaic
re	heat recovered
r	interest rate
s	season
st-in	energy flow into storage
st-out	energy flow out storage
t	each technology
tc	thermal collector

grid level. Electricty, heating and cooling were coordinated by day-ahead dynamic operational optimization. Demand response were enabled as well. Kang [10] proposed a ground source heat pump assisted CCHP system and discussed the impacts of electricity feed-in tariff and carbon tax on system design and dispatch. Facci [11] designed a SOFC based CCHP system and applied in a residential building. The system design capacities have been fitted as a function of capital cost based on different control strategies.

These studies aim to optimize the system for either economic or environmental objectives. Meanwhile other studies analyzed the trade-off between more than one objective by multi-objective optimization approaches. Saman et al. [12] modelled a solar and wind assisted SOFC CCHP system considering cost, emissions and area as objectives simultaneously. Zhang et al. [13] established a MILP model for optimal dispatch of the UK domestic energy supply system as well as optimal scheduling of the home appliances to achieve least operation cost or carbon emissions. Ju [14] optimized a CCHP system by considering four objectives and entropy weighting was applied to assign weights for each objective. Wei [15] utilized NSGA-II (Non-dominated Sorting Genetic Algorithm-II) to optimize the system operation parameters for the objectives of maximizing energy saving and minimizing energy cost.

Except for optimization of the design and dispatch research, other researchers use multi-criteria assessment approaches to evaluate the feasibility of distributed energy system particularly for comparison purposes. Li et al. [2] applied the entropy weighting approach to assign weights when comparing different criteria from different cases. Wu et al. [16] compared the CHP system performance when implemented in Japan and China by an improved GRA approach. Wang et al. [17] utilized a combined AHP and entropy weighting approach to assess the performance of different prime movers for CCHP systems.

It can be seen that some of the researches focused on optimization of distributed energy system by considering dispatch optimization only, while the optimal design issue may not be tackled. Some researchers conducted the multi-objective optimization by only one approach or not mentioned the decision making details. Other researches focused on performance comparison, but the optimization models may relatively