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Multi-objective optimization of a distributed energy network integrated with heating interchange

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ABSTRACT

In this study, a multi-objective MILP (mixed integer linear programming) model has been developed for the optimization of a distributed energy network integrated with heating interchanges. The model allows to determine the energy generation components among various candidates, the site and size of each selected technology, optimal running schedule, as well as optimal lay-out of heating pipelines. Both economic and environmental aspects have been taken into account in the objective function with relative weighting factors. As an illustrative example, the model is applied to a low carbon community including five buildings (hotel, hospital, office, store and apartment) located in Shanghai, China. According to the simulation results, by introducing the distributed energy network, the total capacity of distributed generations is increased, and the overall performances (both economic and environmental ones) of the local area are enhanced. In addition, the sensitivity analyses indicate that the determination of user preference, as well as the fluctuation of energy loads and fuel prices may have considerable influence on the performances of the distributed energy network. Moreover, according to the results of "8 buildings" cases with different building combinations, the rational selection of end-users is of vital importance for the plan and design of a distributed energy network.

1. Introduction

The DES (distributed energy system) has been paid more and more attention due to the urgent need to deal with energy shortage and air pollution problems all over the world. Compared with the conventional centralized energy supply mode, DES is a kind of on-site energy generation system allowing for high energy generation efficiency and avoidance of transmission and distribution losses [1–3]. From a technical point of view, DES can utilize local renewable energy resources such as solar, wind, hydro, geothermal and tidal energy, which are plenty and environment-friendly with zero emissions [4,5]. In addition, CHP (combined heat and power) technologies [6–8] are also widely adopted in DES with high generation efficiencies and low emissions thanks to the simultaneous production of electric and thermal energy without neglecting energy supply service and reliability [9].

On the other hand, in recent years, based on the concept of DES, the DEN (distributed energy network) which allows for energy sharing among various consumers has been proposed. Generally, the DEN may include electricity network, heating network, cooling network, even fuel network or a combination of them. By constructing a DEN, the following benefits can be obtained:

(1) Through the energy interchanges among building clusters, the total energy cost of the whole district rather than a single building can be reduced [10,11].
(2) Taking the advantage of diversified load profiles of various types of building, the energy balance between the supply and demand sides can be achieved easily through the cooperation of neighboring customers. In addition, thanks to the load leveling benefits, the part-load performance may be improved.
(3) For the energy generated can be shared among the consumers, larger energy conversion units will be considered with higher energy generation efficiencies and lower specific capital costs compared with smaller ones [12].

However, in order to achieve the maximum benefits (e.g., energy saving and cost reduction) of the DEN, the optimal design and

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Nomenclature

Symbols

Area	area of solar thermal collector (m^2)
Boimin	minimum capacity of boiler (kW)
Boimax	maximum capacity of boiler (kW)
C	costs ($)
C°	costs with pure economic objective ($)
Cap	capacity of each equipment (kW)
Capchp	capacity of CHP (kW)
Capcc	capacity of compression chiller (kW)
CapBoi	capacity of boiler (kW)
CapTs	capacity of thermal storage (kW)
CLoad	cooling load (kW)
COP	coefficient of performance
Clcc	cooling generated from compression chiller (kW)
CRF	capital recovery factor
CRFchp	capital recovery factor of CHP
CRFpipe	capital recovery factor of pipe
D	days per month (Day)
Dist	distance between the nodes (m)
Echp	electricity generated from CHP (kW)
ELoad	electricity load (kW)
EPur	electricity purchased (kW)
ESa	electricity sold out to the grid (kW)
Eccin	energy input of compression chiller (kW)
EPrice	electricity tariff rate ($/kWh)
ESaPrice	electricity buy-back price ($/kWh)
EM	annual CO_2 emissions (kg)
EM°	CO_2 emissions with pure environmental objective (kg)
EneOut	energy output (kW)
ECI	carbon intensity of electricity (kg CO_2/kWh)
F	objective value
Gprice	gas price ($/kWh)
GCI	carbon intensity of natural gas (kg CO_2/kWh)
HTra	heating transferred (kW)
HBoi	heat generated from boiler (kW)
HLoad	heating load (kW)
HER	heating to power ratio of CHP
Hchp	heat recovered for CHP (kW)
HStc	heat generated from solar thermal collector (kW)
HTs	heat of thermal storage tank (kWh)
IR	interest rate (%)
LifeN	lifetime of each equipment (Year)
M	an appropriate upper bond
OMFix	unit fixed O&M cost other than CHP ($/kW)
OMVar	unit variable O&M cost other than CHP ($/kWh)
OMFixC	unit fixed O&M cost of CHP ($/kW)
OMVarC	unit variable O&M cost of CHP ($/kWh)
OMP	O&M cost for heating networks ($/m)
OR	visiting order of each node
Rad	solar radiance (kW/m^2)
Tsmin	minimum capacity of thermal tank (kWh)
Tsmax	maximum capacity of thermal tank (kWh)
UCDer	unit cost of distributed generator other than CHP ($/kW)
UCchp	unit cost of CHP ($/kW)
UCpipe	unit cost of heating pipeline ($/m)

Binary variables

In,Out	0–1 variable
x	selection of heating pipeline
y	selection of CHP
yb	selection of boiler
yTs	selection of thermal tank

Greek letters

α	weighting factor of annual costs
β	weighting factor of annual emissions
λ	heat to power ratio
η	efficiency (%)
σ	energy loss ratio during transfer (%)
γ	power efficiency of CHP (%)

Superscripts

boi	boiler
chp	combined heat and power
cc	compression chiller
in	heat delivered to tank
out	heat released from tank
pipe	heating pipe
stc	solar thermal collector

Subscripts

elec	electricity
gas	city gas
h	duration hours in a day
i, j	index of end-use node
inv	investment
k	index of CHP unit
m	months
om	operation and management
obj	objective
rev	revenue from electricity sold out to the grid
s	index of distributed generator except CHP
total	the whole system

running scheduling is necessary but complicated. In detail, the optimal design refers to the selection of rational equipment components and corresponding capacities, the locations of selected equipments as well as optimal lay-out of energy transferring infrastructures. On the other hand, optimal running scheduling of the DEN includes hourly energy generation of each producer, load allocation of all consumers as well as energy interchanges among the users in each time period. Several studies have been conducted on the above mentioned key points of the DEN. Wakui et al. [13] dealt with the optimization problem of the DEN integrated with CHP units for residential buildings, based on a MILP (mixed integer linear programming) method. Omu et al. [5] introduced a DENO (distributed energy network optimization) model and applied it to a mixed used development consisted of various types of buildings. Yang et al. [1] developed an advanced and complex MILP model for the optimal design and operation of a DEN considering residence, mall, hotel and hospital. In Ref. [14], a cost minimization model for a DES allowing for heating transfer was developed, whereas the model regarded equipment capacities as continuous variables.

Generally, in previous studies, the MILP model has been widely employed for the optimization of the DEN with economic objective function. Nowadays, due to growing concerns on the environment