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Operation optimization of a distributed energy system considering energy costs and exergy efficiency

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ABSTRACT

With the growing demand of energy on a worldwide scale, improving the efficiency of energy resource use has become one of the key challenges. Application of exergy principles in the context of building energy supply systems can achieve rational use of energy resources by taking into account the different quality levels of energy resources as well as those of building demands. This paper is on the operation optimization of a Distributed Energy System (DES). The model involves multiple energy devices that convert a set of primary energy carriers with different energy quality levels to meet given time-varying user demands at different energy quality levels. By promoting the usage of low-temperature energy sources to satisfy low-quality thermal energy demands, the waste of high-quality energy resources can be reduced, thereby improving the overall exergy efficiency. To consider the economic factor as well, a multi-objective linear programming problem is formulated. The Pareto frontier, including the best possible trade-offs between the economic and exergetic objectives, is obtained by minimizing a weighted sum of the total energy cost and total primary exergy input using branch-and-cut. The operation strategies of the DES under different weights for the two objectives are discussed. The operators of DESs can choose the operation strategy from the Pareto frontier based on costs, essential in the short run, and sustainability, crucial in the long run. The contribution of each energy device in reducing energy costs and the total exergy input is also analyzed. In addition, results show that the energy cost can be much reduced and the overall exergy efficiency can be significantly improved by the optimized operation of the DES as compared with the conventional energy supply system using the grid power only.

1. Introduction

With the growing demand of energy on a worldwide scale, improving the efficiency of energy resource use has become one of the key challenges. The consumption of primary energy in buildings accounts for more than one third of the total world's energy consumption [1]. Most of the energy used in buildings is required to maintain room temperatures at around 20–26 °C, or to heat water at a temperature around 60 °C. These thermal demands are commonly supplied by electricity or fossil sources [1,2]. Assessments of energy use in buildings are usually based on quantitative considerations by using the First Law of Thermodynamics [1]. Concerning the conservation of energy, the First Law, however, does not take into account the degradation of the energy quality that takes place when high-quality energy resources, such as electricity or fossil fuels, are used to satisfy low quality thermal demands.

Exergy, derived from the Second Law of Thermodynamics, is a measure of the energy quality. It is the maximum amount of work that can be obtained from an energy flow as it comes to the equilibrium with the reference environment [1,3–7], and can be viewed as the potential of a given energy amount. Unlike energy, exergy is not subject to conservation (except for reversible processes). Rather, exergy is destroyed due to irreversibilities in any real process [8]. Exergy analysis was used for performance evaluation of single energy systems, e.g., geothermal systems [9–11], cogeneration systems [12–15], renewable energy sources [16], and heat recovery steam generators [17], with the aim to find the most rational use of energy. The performances of different options of

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Nomenclature

A	area (m^2)
$\dot{B}$	biomass mass flow rate (kg/h)
c	constant in Eq. (29) (kW h/$)
$\dot{C}$	cooling rate (kW)
COP	coefficient of performance
$Cost$	total energy cost ($)
DR	maximum ramp-down rate (kW)
ex_{bio}	specific chemical exergy of biomass (kW h/kg)
ex_{gas}	specifical chemical exergy of natural gas (kW h/Nm^3)
$\dot{E}$	electricity rate (kW)
Ex	exergy (kJ)
$\dot{Ex}$	exergy rate (kW)
F_{obj}	objective function
F_q	Carnot factor
$\dot{G}$	natural gas volumetric flow rate (Nm^3/h)
$\dot{G}_T$	total solar irradiance (kW/m^2)
$\dot{H}$	heating rate (kW)
H	thermal energy (kW h)
k	generation level of the energy device (kW)
LHV_{bio}	lower heat value of biomass (kW h/kg)
LHV_{gas}	lower heat value of gas (kW h/Nm^3)
P_{bio}	biomass price ($/t)
P_{gas}	natural gas price ($/$Nm^3$)
P_{grid}	electricity price ($/kW h)
$\dot{Q}_{GT,ex}$	heat rate made available by the exhaust gas (kW)
t	time (h)
T	temperature (K)
UR	maximum ramp-up rate (kW)
x	binary decision variable

Greek symbols

Δt	length of the time interval (h)
ε_{gen}	exergy efficiency of electricity generation
ς	exergy factor
η	efficiency
μ	percent heat loss rate of the gas turbine
ξ	gas turbine exhaust fraction
ϕ_{sto}	storage loss fraction
ψ	overall exergy efficiency
ω	weight in Eq. (29)

Superscript/subscripts

0	reference
abs	absorption chiller
bio	biomass
boil	boiler
buy	bought
CCHP	combined cooling, heating and power
coll	collector
dem	demand
DHW	domestic hot water
di	directly provided by natural gas
e	electricity
ED	energy device
EH	electrical heater
ex	exhaust gas
gas	natural gas
GT	gas turbine
HP	heat pump
HR	heat recovery
in	input
max	maximum
min	minimum
out	output
req	required
SC	space cooling
SH	space heating
solar	solar
source	energy resource
sto	thermal storage
th	thermal

Acronyms

CCHP	combined cooling, heating and power
DES	distributed energy system

energy supply systems to meet building demands were evaluated and compared in terms of exergy efficiencies in [18–20]. The concept of exergy was introduced to the building environment by Björk et al. [21], Kilkiş [22] and Molinari [23,24]. In buildings, energy demands are characterized by different energy quality levels. Since the required temperatures for space heating and cooling are low, the quality of these energy demands is low. The energy quality needed for the production of domestic hot water at about 60 °C is slightly higher than that for space heating or cooling. For electrical appliances and lighting, the highest possible quality of energy is needed. Exergy analysis may promote the matching of quality levels of supply and demand, by covering if possible low quality thermal demands with low exergy sources, e.g., solar thermal or waste heat of power generation processes, and electricity demands with high exergy sources. In this way, the waste of high-quality energy resources can be significantly reduced. Therefore, exergy modeling explicitly exposes the irreversibility aspect of energy use, and exergy optimization then allows increasing world's sustainability, crucial in the long run, through efficient use of energy while considering energy qualities.

A Distributed Energy System (DES) refers to an energy system where energy is made available close to energy consumers, typically relying on a number of small-scale technologies [25]. In recent years, developing DES has attracted much interest. One of the benefits of DESs is the possibility to integrate different energy resources, including renewable ones [26–30], as well as to recover low-temperature waste heat for thermal use [31]. In these applications, DESs, as the smallest units to match the quality levels of supply and demand, provide a unique opportunity to obtain the benefits of exergy analysis. However, most of the studies in the literature are focused on the operation optimization of DESs to reduce energy costs, which is essential in the short run. Among them, integrated optimization of energy devices and energy processes of a small eco-community was carried out in Yan et al. [32] to reduce the total daily energy cost. The solution methodology used was branch-and-cut. A mixed-integer optimization model for scheduling multiple energy devices connected to a low energy building was developed in Guan et al. [33] to minimize the overall costs of electricity and natural gas. The problem was also solved by branch-and-cut. Beyond minimizing costs only, optimized operation strategies to reduce energy costs and CO_2 emissions were analyzed. In [34], a mixed-integer model for a small building cluster was established, and the surrogate Lagrangian relaxation method was used to solve the multi-objective problem. In [35], a