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A two-level multi-objective optimization for simultaneous design and scheduling of a district energy system

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HIGHLIGHTS

- A multi-level procedure is proposed to optimize a decentralized energy district.
- Optimal layout (connection of buildings) of the district is considered in the model.
- Type, size and site of the district and backup technologies are taken into account.
- An exemplary case study with eight buildings is dedicated for more clarification.
- 59% emission reduction and 75% cost reduction were achieved.

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ABSTRACT

This paper reports the development of a two-level optimization methodology to help design a tri-generation system for a given district which satisfies the heating, cooling, and hot water demands and at the same time, minimize the annual total costs and CO_2 emissions. An optimization methodology is proposed and tested on a virtual district with eight buildings where three of them can host the district technologies including heat pump, gas engine, and lake cooling. Within the building, some backup technologies may be implemented including an air/water heat pump, a water/water heat pump, a boiler, and electric chillers. Analysis of the Pareto optimal frontier results in several distinct groups of configuration based on the selected district conversion technologies and their capacities. Solution to the sub-problems including design and operation of the district energy system is carried out by applying a Mixed Integer Programming (MIP) technique. Several different clusters are defined and studied regarding the cost and CO_2 emission. A reference configuration is defined for the purpose of comparison in which electricity is supplied by the grid, heating and hot water by a boiler, and cooling by an electric chiller. Compared to this configuration, the best solution with respect to CO_2 emissions causes 59% emission and 75% cost of the reference configuration. In this case, 53% of the total cost is associated with the initial investment cost while the rest 47% is associated with the operational cost. The optimal configuration with respect to the annual costs causes 86% more emission than the reference configuration and 38% less annual costs. In this case, 22% of the total cost is associated with initial investment cost while 78% of the total cost is associated with the operational cost. Implementation of a two-pipe system instead of a four-pipe system results in nearly 5% reduction in total annual cost.

1. Introduction

The rational design and planning of district energy systems have a pivotal role to achieve maximum energy saving/efficiency and maximum economic benefits for implementation of such systems [1]. However, optimization of a district energy system is a complex task for several reasons. First, it includes both spatial aspect associated with the location and temporal aspect associated with consumption, production, and price profiles. Second, many combinations can be considered for locations of buildings, size of energy units, and linkage between the end users among possible candidates. Third, the consumption profiles vary in a stochastic manner during the day and from day to day requiring much more sophisticated techniques to tackle the multi-period problem [2]. Finally, temperature requirement of some buildings may vary from others during different periods even for the same buildings [3]. This study tries to achieve some solutions for the first and second issues raised above focusing on the second challenge. These issues can be represented by (1) optimal integration of technologies, (2) optimal

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Nomenclature

Latin symbols

A	surface area of the pipe (m^2)
An	Annuity factor
b^{grid}	Selling price of electricity (US $)
C	Annual cost (US $)
C_{water}	Isobaric specific heat of water (J/kg K)
CO_2	CO2 emission (kg/year)
d	Pipe diameter (m)
D	Duration (hour)
$Dist_{i,j}$	Distance between nodes i and j (m)
$\dot{E}$	Electricity flow rate (W)
f	Friction coefficient in the pipes
Fm^i	Maintenance factor for device i
I	Income (US $)
K	Pipe thermal conductivity ((W/mK)
Ms^i	Marshall-Swift factor for the desired accounting year for device i
N	Lifetime (years)
$\dot{P}$	Thermal energy flow (W)
p_{loss}	Pressure losses per meter long pipe (Pa)/m
R	Consumption rate (W)
r	Interest rate of a device i
S	Design size (W)
T	Temperature (°C)
$X_{i,j}$	Binary variable to represent connection between the nodes
$Y_{i,j}$	Binary variable to represent the existing connections between the nodes

Greek symbols

$\varkappa$	part load factor
η	efficiency
υ	velocity (m/s)
ρ	density (kg/m^3)

Subscripts and superscripts

Aw	air-water heat pump
build	from distribution network
C	cooling
Cn	cooling network
cond	condenser
cons	towards consumer
Cr	cooling return
cs	cooling supply
ct	cooling technology
el	electricity
end	end of a one meter long pipe
evap	evaporator
exp	exported
Fix	fixed cost
G	ground
GE	gas engine
H	heating
hex	heat exchanger
Hm	heating mode
hn	heating network
hP	heat pump
hr	heating return
hs	heating supply
ht	heating technology
HW	hot water
i	device i
i,j	node number
k	node number
loss	energy loss in network
max	maximum capacity
min	minimum capacity
prop	proportional cost
t	period number
tech	technology used
ub	upper bound
ww	water-water heat pump

Abbreviations

C	configuration
CHP	combined heat and power
COP	coefficient of performance
DHS	district heating system
HP	heat pump

configuration of the network, and (3) optimal operation. In other words, if several power or heating sources are available, their integration must take into account their characteristics, operating costs and technical constraints. As a result, even with a limited number of units, the definition for the site of the technologies along with the planning strategy controlling the district plants to run at minimum cost or exploit the maximum possible share of renewables is not a simple task, or optimizing other objective functions. The best network might as well be the one causing the least environmental damage, or the most economical one, in terms of natural resources or money.

Several studies can be found which attempts to find an answer to some or part of optimal integration, optimal configuration, optimal running mentioned above as described in this paragraph.

Some earlier research work focused on the distribution system. For example, Vesterlund and Dahl [4] employed ReMIND and CPLEX to tackle the MILP problem of the hydraulic performance of a district distribution system. They introduced a new process for integration technique, which allows the modeling of DHSs with loops (closed path for a fluid flow). This was done without introducing any simplification or modification to their physical structure, modeling of DHSs containing of multiple sources of thermal energy production and redesign of the DHS structure, in particular to add or remove consumers. Jie et al. [23] proposed an analytical model to find the optimal pressure drop and related minimum annual cost for the distribution network in a district heating based on operating variables and different strategies. Wang et al. [7] employed Newton's method for a NLP problem to minimize the cost of a district heating system (an N-floor building) based on separate mass flow rate (pumping cost) and thermal conductance (heat exchanger cost). In each case, the value of other objective assumed to be constant. Jie et al. [11] introduced an optimization model to minimize the sum of pumping and heat loss costs for an existing district heating system. Four different strategies were considered and compared based on considering constant or variable flow rates for primary and secondary sides of the district. Fang et al. [14] proposed a static model to find the optimal plant supply temperatures and load allocation among the systems based on the real-time end-user measurements to optimize the heat production planning. Automated meter reading data was employed to approximate the heat losses, flow rates, and nodal temperatures within the network. Kim et al. [15] considered several district systems simultaneously. They tackled the