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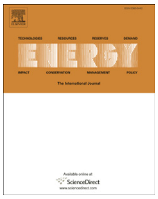

Integration of distributed energy storage into net-zero energy district systems: Optimum design and operation

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ABSTRACT

A net-zero energy district is any neighborhood where the consumption of the buildings is offset by on-building generation on an annual basis. In this study, a net-zero energy district is identified among the set of optimal solutions and the effects of storage on its performance is investigated. It is assumed the model simultaneously optimizes the location of host buildings (energy generators), type of technologies and associated size, and the energy distribution network layout together with the optimal operating strategy. The optimization model addresses all technologies with a special focus on the effect of application of energy storage. Two types of energy storage are considered inside each building: thermal energy storage (hot water tank) and electrical energy storage (battery bank). The model is applied to the new part of a district energy system located in Switzerland. The best integrated district energy systems are presented as a set of Pareto optimal solutions by minimizing both the total annualized cost and equivalent CO_2 emission while ensuring the reliable system operation to cover the demand. The results indicated that selection of the proposed optimal district energy system along with the storage brings great economic and environmental benefits in comparison to all other scenarios (conventional energy system, stand-alone system, and net zero-energy without storage).

1. Introduction

Similar to the electricity production system situated inside or close to end-users, district energy system can simultaneously supply power, heating, and cooling in an efficient way to cover the demands of local consumers [1]. Significant benefits are provided by such systems, namely saving primary energy by heat recovery, low heat and power transmission loss, and improved energy and exergy efficiencies [2,3]. The rational design and operation strategy of district energy systems play a key role to achieve maximum economic benefits and provide best energy saving strategy. The design of a district energy system calls for the rational creation of its structure through choosing the suitable technologies from numerous alternatives together with the appropriate number and size of each equipment to reliably cover the energy demands of the end-users [4,5]. Meanwhile, the best management strategy and load allocation for the selected technologies have great importance, which depends heavily on temporal variation of buildings energy requirements [6]. Energy simulation tools typically fail to take into consideration all the parameters simultaneously. For example, HOMER, a well-known tool has storage technologies including batteries, flywheels and hydrogen without any thermal energy storage. The tool has a limited number of thermal units that are typically simplified: CHP, boiler, and biomass [7]. Therefore, to perform such a complicated task, mathematical programming approaches have been employed for a wide range of applications to make informed decisions about the optimal design and management of district energy systems [8]. Linear programming (LP) and mixed-integer linear programming (MILP) are the two most common approaches employed by the designers and engineers because the problem usually incorporates thousands of variables [9]. Vesterlund and Dahl [10] focused on the loop in the distribution network of a district. They introduced a new methodology to simplify the analysis of the complex networks with several loops to find the bottlenecks. In a study done by Wang et al. [11], an improved optimization model was proposed to provide smoother operation of cogeneration units by imposing a new constraint for power ramping. Carpaneto et al. [12] investigated integration of solar energy into existing districts to minimize the management

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Nomenclature

Latin symbols

A	Surface area of PV (m^2)
E	Power flow (kW)
p	Price of energy carrier
C	Cost per unit production (€/kWh for all technologies except PV and (€/kWh.m^2 for PV)
G	Nominal capacity (kW)
d	Distance (m)
O	Binary variable for chiller
Q	Heat flow (kW)
CT	Carbon tax (€/kWh)
B	Binary variable for thermal storage
SOC	State of the charge (kWh)
r	Interest rate
I	Carbon intensity (kg/kWh)
X	Binary variable for CHP
Y	Binary variable for pipeline connection
Z	Binary variable for chiller
U	Binary variable for boiler
V	Visiting order
W	Binary variable for selling/purchasing power
T	Binary variable for wire connection
S	Solar irradiation (kW/m^2)
R	Binary variable for battery bank
F	Objective function

Greek symbols

σ	Percentage of heat loss
η	Efficiency
ζ	Heat to power ratio
θ	Inclination angle
Δ	Duration (hour)
α	Interest rate

Subscripts and superscripts

tot	Total
Inv	Investment
op	Operation
car	Carbon emission
elec	Electricity demand
pur	Purchased
sel	Soled
i,j	Building number
PV	Photovoltaic array
B	Boiler
CHP	Cogeneration unit
max	Maximum capacity
n	Number
BB	Battery bank
emi	Emission
K	Type of CHP unit
Sol	Solar
chil	Chiller
S	Season
T	Period
grid	Utility grid
Gas	Fuel (natural gas)
Lo	Lower bound
Up	Upper bound
used	Self-used energy
eat	Heating demand
M	Number of chillers
HS	Heat storage
cost	Total annualized cost

Abbreviations

COP	Coefficient of performance
CHP	Combined heat and power
DHC	District heating and cooling
CRF	Capital recovery factor

cost by considering collector heat loss and produced power. Wang et al. [13] employed a conventional simple optimization algorithm to reduce the operation cost of pumping and heat exchanger in a high-rise apartment building. An operational optimization is carried out by Wang et al. [14] focusing on characteristics of the district energy system considering pumps with variable speed. A study on low-temperature district heating system is performed by Tunzi et al. [15] in which the operating temperature of the plate radiators is reduced. It also concluded that overall heat distribution losses and fuel consumption is lowered by 10%. In a similar work, Park et al. [16] found the optimized supply temperature in a secondary distribution network of a low district heating system. Supply temperature affects the costs related to heat loss, pumping energy, and required area of the heat exchangers and therefore an optimum solution exists that minimizes the total cost. Schweiger et al. [17] introduced a two level optimization model, which split the control problem into discrete and continuous sub-problems. The model is applied to optimize the thermal and hydraulic behavior of a district heating and cooling system. In another study based on decomposition technique, Sameti and Haghighat [4] developed a methodology to simultaneously optimize the design and operation of a tri-generation district. The authors showed the effectiveness of their model on a virtual case study focusing on supply and return temperatures as well as selecting components. In a study on district cooling, Khir and Haouari [18] developed a computational non-linear optimization model to achieve the optimum size of the chillers, cold thermal storage, and structure of the primary distribution pipeline. Temperature and pressure drops were also considered in their hydraulic model. Zhou et al. [19] carried out a comparative analysis of constant-efficiency and off-design characteristics for a tri-generation district to achieve lowest overall cost of the system. Powell et al. [20] introduced a dynamic optimization model to obtain the appropriate time of charging/discharging for a thermal energy storage and manage cooling and power load shifting. Jie et al. [21] investigated the variability of flow rates in both primary and secondary energy distribution networks on the pumping cost and on the cost associated with heat losses in an existing district. Jiang et al. [22] optimized the fuel consumption of an integrated system comprising of a wind turbine as one of the suppliers for an electric water heater together with a solar water heater and a gas-fired boiler. Ren et al. [23] put forward an optimization model to find the best operational management of a district power system composed of PV arrays, fuel cell, battery bank, and utility grid to achieve the most beneficial economic and environmental level. In a similar study done by Sameti and Haghighat [24], the capital cost of designing a new system is also taken into account where the interaction of heating and power is also analyzed. Fang et al. [25] developed a static model using genetic algorithm (GA) to optimize the district supply temperatures and load allocation among the plants based on the real-time end-