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Research Paper

Exergy-based operation optimization of a distributed energy system through the energy-supply chain

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HIGHLIGHTS

- Exergy-based operation optimization of a Distributed Energy System.
- Exergy losses modeled for the energy devices at the energy conversion step.
- Multi-objective optimization problem to reduce energy costs and exergy losses.
- Problem solved by surrogate Lagrangian relaxation combined with branch-and-cut.
- Reduced waste of high-quality energy resources by reduction of exergy losses.

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ABSTRACT

Developing sustainable energy systems is crucial in today's world because of the depletion of fossil energy resources and global warming problems. Application of exergy principles in the context of energy supply systems may achieve efficient energy-supply chains and rational use of energy in buildings. This paper presents an exergy-based operation optimization of a distributed energy system by considering the whole energy-supply chain from energy resources to user demands. The problem is challenging in view of the complicated interactions of energy devices and the modeling of exergy losses. To capture these complicated interactions, energy networks are established with exergy losses modeled at the energy conversion step, which accounts for the largest part of the total exergy loss in the whole energy-supply chain. A multi-objective mixed integer programming problem is formulated. The problem is efficiently solved by the novel integration of surrogate Lagrangian relaxation and branch-and-cut. 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 exergy loss occurring at the energy conversion step. Results demonstrate that the use of high-quality energy resources is reduced by the reduction of exergy losses, leading to sustainability of energy supply systems.

1. Introduction

Developing sustainable energy systems is becoming more and more important in today's world because of the depletion of fossil energy resources and the related global warming problems. Therefore, high-quality energy carriers, such as fossil fuels and electricity, should be efficiently used [1]. Buildings are responsible for more than 40% of the total final energy consumption on a worldwide scale [2]. A significant share of this energy consumption is for space heating (SH) and cooling, and domestic hot water (DHW) demands. These are low-quality energy demands because of the associated temperatures required. However, thermal demands in buildings are commonly met by high-quality energy resources. There is great potential in energy-management of energy supply systems to attain efficient energy-supply chains and rational use of energy in buildings [3].

Current analyses and optimization methods for energy-management of energy supply systems do not distinguish different qualities of energy flows. In thermodynamics, the quality of an energy carrier is measured by exergy. Exergy is defined as the maximum theoretical work that can be obtained from an energy flow, as it comes to the equilibrium with the reference environment [1,3–7]. The concept of exergy was introduced in building

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efficiency studies by international research projects, such as ECBCS Annex 37 [5], and Annex 49 [1]. Several studies on the exergy analysis of energy supply systems for the building environment are also found in recent years [6,8–10].

A distributed energy system (DES) is an energy system where energy is made available close to energy end-users [11]. DESs provide a unique opportunity to show the benefits of the exergy analysis for preserving high-quality energy resources, since several energy devices convert a set of primary energy carriers (e.g., electricity, solar energy, natural gas) with different energy quality levels to satisfy end-user demands with different energy quality levels. In terms of DESs, most of the studies in the literature are focused on the operation optimization of DESs to reduce energy costs [12–14], which is essential in the short run. The optimized operation strategies of a DES were obtained in a previous work [15] to reduce the total daily energy cost and increase the total exergy efficiency. For simplicity, the total exergy input to the DES and the total exergy output required to meet the energy demands were considered instead of the exergy input and output of each energy device in the energy-supply chain.

This paper presents an exergy-based operation optimization of a DES through the energy-supply chain from energy resources to user demands (electricity, SH and DHW demands are considered), without neglecting the energy costs. The main goal is to obtain the optimized operation strategies of the DES to reduce the total energy costs and the total exergy loss occurring at the energy conversion step, which accounts for the largest part of the total exergy loss in the whole energy-supply chain. By reducing these exergy losses, the use of high-quality energy resources can be reduced, leading to sustainability of energy supply systems.

The optimization problem is challenging since several energy devices convert a set of input energy carriers, such as natural gas, electricity, and solar energy, into output energy carriers, such as heat and electricity, with complicated interactions among them; the exergy of thermal energy is directly related to the temperature and the mass flow rate of the corresponding energy carrier, and the problem is nonlinear. To capture the complicated interactions, energy networks are established from energy resources to user demands, based on the physical structure of the energy-supply chain. Exergy losses are then modeled for the energy devices at the conversion step based on the networks to make visible where and how much exergy is lost. A multi-objective mixed-integer problem is formulated. The objective is to minimize a weighted sum of the total energy cost and exergy losses at the energy conversion step while satisfying given time-varying user demands. Surrogate Lagrangian relaxation and branch-and-cut are integrated in a novel way for a speedy and near-optimal performance. The Pareto frontier, consisting of the best possible trade-offs between the economic and exergetic objectives, is obtained. Results show that the use of high-quality energy resources can be reduced by the reduction of exergy losses, leading to sustainability of energy supply systems.

2. Problem formulation

To match the solution methodology, the surrogate Lagrangian relaxation combined with branch-and-cut method, a separable and linear formulation, is preferred to solve the problem efficiently. The energy-supply chain under consideration consists of energy conversion devices, including gas turbine and heat recovery boilers, as the combined heat and power (CHP) system, solar thermal plant, auxiliary natural gas boilers, and heat pump; thermal energy storages, distribution devices (e.g., water pipes) as well as terminal devices (e.g., fan coils for SH) are also considered as shown in Fig. 1. Electricity is 100% exergy (fully convertible into useful work), while the exergy of thermal energy is directly related to the temperature and mass flow rate of the corresponding energy carrier. The energy networks for space heating and domestic hot water demands need to be established based on the physical structures of water pipes, valves, mixers, etc.

The general structure of the energy and exergy modeling and common constraints of energy devices are first described as follows.

Capacity constraints. The energy generation rate (e.g., electricity and heat) of the device, $R_{ED}(t)$, should be within its minimum and maximum values if it is on (xED (t) = 1):

$$x_{ED}(t)R_{ED}^{\min} \le R_{ED}(t) \le x_{ED}(t)R_{ED}^{\max} \quad (1)$$

Ramp rate constraints. The variations in energy generation rates between two successive time intervals should be within the ramp-down, DRED, and ramp-up, URED:

$$-DR_{ED} \le R_{ED}(t) - R_{ED}(t-\Delta t) \le UR_{ED} \quad (2)$$

where Δt is the length of the time interval.

Energy consumption. The input rate of the energy source, $S_{ED}^{in}(t)$, required by the energy device to provide the output energy rate, $R_{ED}(t)$, is:

$$S_{ED}^{inp}(t) = R_{ED}(t)/\eta_{ED} \quad (3)$$

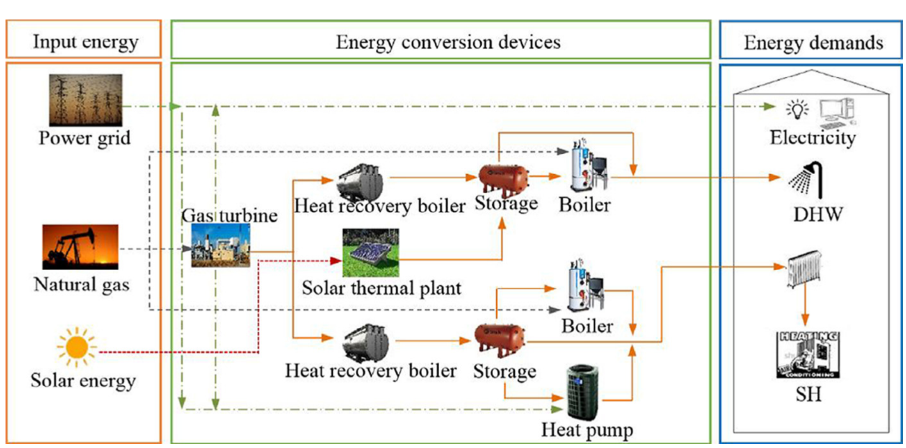

Fig. 1. Scheme of the energy-supply chain.

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