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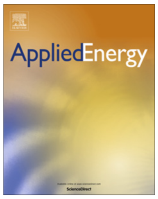

# Interactions of district electricity and heating systems considering time-scale characteristics based on quasi-steady multi-energy flow

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## HIGHLIGHTS

- Interaction mechanisms of district electricity and heating systems are analyzed.
- The interaction process is divided into four quasi-steady stages.
- A quasi-steady multi-energy flow model is proposed and calculated.
- A heating network node type transformation technique is developed.
- Attention should be paid on the fast hydraulic process and slow thermal process.

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## ABSTRACT

Integrated energy systems (IESs) are under development for a variety of benefits. District electricity and heating systems (DEHSs) deliver electricity and heat, the most common energy demands, to end-users. This paper studies the interactions in a DEHS considering the time-scale characteristics. Interaction mechanisms of a DEHS are analyzed. A disturbance in one system influences another system through coupling components, depending on the disturbance, operating characteristics, and control strategies. A model of the main components in DEHSs is presented. The time scale characteristics are studied based on a dynamic comparison of the different components. Then the interaction process is divided into four stages; each is a quasi-steady state. A quasi-steady multi-energy flow model is proposed and calculated, with a heating network node type transformation technique developed. A case study with detailed results and discussion of 3 types of disturbance is presented to verify the methods. The results present the interactions between the electricity and the system. It is suggested that attention should be paid both on the fast hydraulic process and slow thermal process for system security and economic operation.

## 1. Introduction

Integrated energy utilization is an effective way to improve energy efficiency, reduce $CO_2$ emissions, and increase renewable energy penetration, which are among the most urgent energy topics worldwide. Thus, integrated energy systems (IESs), also known as multi-energy systems and multi-carrier energy systems, are under rapid development [1–6]. IESs generally cover at least two individual systems: electricity, heating, cooling, gas, or transportation systems. Coupling components, such as combined heat and power (CHP) units, combined cooling, heating, and power (CCHP) units, heat pumps (HP), electric boilers (EB), electric chillers, gas or steam absorption chillers, fuel cells, and thermal and photovoltaic collectors, interconnect individual energy systems into an integrated energy system.

As the coupling between different energy systems becomes tighter, traditional methods used to study each individual energy system separately can no longer meet the requirements of IESs. Many researchers have studied the planning, scheduling, optimization, and evaluation of IESs [7–18]. Liu et al. proposed a new operation strategy for CCHP systems with hybrid chillers [7]. Ren and Gao developed a mixed-integer linear programming (MILP) model for the integrated planning and evaluation of distributed energy systems [10]. Geidl and Andersson studied the optimal power flow of multi-energy carriers using energy hub concepts [14]. A modeling approach to multi-energy systems in buildings is described in [15]. District heating systems have attracted much attention, and can be developed into multi-energy systems [16]. Denmark leads in renewable energy utilization, and its goal of being independent

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## Nomenclature

*Indices and parameters*

| | |
|---|---|
| $\alpha$ | absorptivity of the absorber plate for solar radiation |
| $\lambda$ | overall heat transfer coefficient per unit length (W/(m K)) |
| $\eta_e$ | electrical efficiency of an extraction steam turbine CHP unit in full condensing mode |
| $\eta_p$ | efficiency of a circulation pump |
| $b$ | parameter of heat transfer coefficient of a radiator |
| $c_m$ | heat to power ratio |
| $g$ | acceleration of gravity (kg m/s$^2$) |
| $i, j$ | node no. of the electricity or heating network |
| $q_v$ | volumetric heat index of a building (W/m$^3$ °C) |
| $\mathbf{A}$ | network incidence matrix |
| $\mathbf{B}$ | loop incidence matrix |
| $B_{ij}$ | imaginary part of element ($i, j$) in node admittance matrix |
| $C_p$ | specific heat of water (J/(kg K)) |
| $F$ | total heat radiating area of the radiator (m$^2$) |
| $G_{ij}$ | real part of element ($i, j$) in node admittance matrix |
| $K$ | resistance coefficient of each pipe |
| $L$ | pipe length (m) |
| $V$ | peripheral volume of a building (m$^3$) |
| $Z$ | $Z$ ratio that describes the trade-off between heat supplied to site and electrical power |

*Variables*

| | |
|---|---|
| $\theta_{ij}$ | voltage angle difference of node $i$ and $j$ (rad) |
| $\phi_1$ | heat transferred from the network to the radiators (MW) |
| $\phi_2$ | heat supplied to building (MW) |
| $\phi_3$ | heating load of building (MW) |
| $\phi_{CHP}$ | useful heat output of a CHP unit (MW) |
| $h_f$ | vector of head loss within pipes (m) |
| $\dot{m}$ | mass flow rate within each pipe (kg/s) |
| $\dot{m}_q$ | injected mass flow rate at each node (kg/s) |
| $\dot{m}_{in}$ | mass flow rate within a pipe coming into the node (kg/s) |
| $\dot{m}_{out}$ | mass flow rate within a pipe leaving the node (kg/s) |
| $F_{in}$ | fuel input rate (MW) |
| $H_p$ | pump head (m) |
| $P$ | electrical real power (MW) |
| $P_{con}$ | electricity generation of an extraction steam turbine CHP unit in full condensing mode (MW) |
| $P_{CHP}$ | electricity generation of a CHP unit (MW) |
| $P_p$ | electricity consumed by a circulation pump (MW) |
| $Q$ | electrical reactive power (MVar) |
| $T_a$ | ambient temperature of pipes (°C) |
| $T_{end}$ | temperature at the end node of a pipe (°C) |
| $T_{in}$ | temperature of flow at the end of an incoming pipe (°C) |
| $T_n$ | indoor temperature (°C) |
| $T_{out}$ | mixture temperature of a node (°C) |
| $T_O$ | return temperature at the outlet of a node before mixing in the return network (°C) |
| $T_w$ | ambient temperature of buildings (°C) |
| $T_S$ | supply temperature at a node in the supply network (°C) |
| $T_{start}$ | temperature at the start node of a pipe (°C) |
| $V$ | voltage amplitude (V) |

of fossil energy sources imposes great demands on all energy subsystems [2]. Quelhas et al. presented a multi-period generalized network flow model for an IES in the United States [17,18]. Chaudry et al. explored the combined gas and electricity network expansion planning [19].

Electricity and heat are the most common end-user energy demands. In traditional electricity systems, some large CHP units supply electricity and heat simultaneously. Because other generators, such as thermal power units, are usually sufficient to maintain the electrical power balance. CHP units seldom participate in the electrical power balance service to satisfy heat supply as a priority. This results in weak coupling between the electricity system and the heating system. However, as greater numbers of uncertain renewable energy generators are integrated into the electricity system, the flexibility of traditional generators is insufficient, while the flexibility of the heating system is considerable [20,21]. To take advantage of this flexibility, CHPs are required to play more active roles in system operation. Moreover, the coupling between electricity systems and heating systems is increasing, especially at the district level. To achieve the benefits of IESs, the coordination operation and interactions among individual systems are necessary.

Many papers have studied the economic optimization of electricity and heating systems, but little attention has been paid to the security of IESs, especially in the operation stage. The heating network model is usually omitted from economic studies. When the system is large, most energy is delivered by networks. It is not appropriate to omit any network from the model. Electricity networks and heating networks have been studied maturely in each energy area separately. Liu et al. [12,13] endeavored to combine the analysis of electricity and heating networks, proposing two combined analysis methods to calculate the energy flow. However, the time-scale characteristics of the electricity and heating system, which are quite different from an individual electricity system, were not considered. The dynamic of a heating system results in prolonged interaction process between the two systems.

This paper focuses on a district electricity and heating system (DEHS), in which CHP units dominate and are responsible for supplying the electrical load and the heat load of the whole system, especially when the system is isolated from external systems. At the district level, the electricity and heating coupling is of great importance for improving energy efficiency. In past years, a greater number of coupling components have been installed, resulting in a stronger coupling between the electricity and heating systems. DEHS is an integrated system, which is considerably more complex than an individual energy system. The interactions between the electricity system and the heating system are a new topic and also complicated. It is of great significance to study the interactions in a DEHS to take full advantages of the coupling.

The physical interactions of the DEHS, related to the system security and economic operation, are studied in this paper. The interaction mechanism by which a disturbance in one system influences other systems and the original system where the disturbance occurs is analyzed. The influences are conveyed through coupling components, depending on the disturbances, operating characteristics, and control strategies. A model of the main components in the DEHS is presented. The time-scale characteristics of the DEHS are further studied, based on a comparison of the dynamic of various components. A quasi-steady multi-energy flow model is proposed and calculated considering critical system constraints by developing a heating network node type transformation technique. The word "*quasi-steady*" in this paper differs from "*steady*" by

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