Applied Energy xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

# Optimal operation of the integrated electrical and heating systems to accommodate the intermittent renewable sources

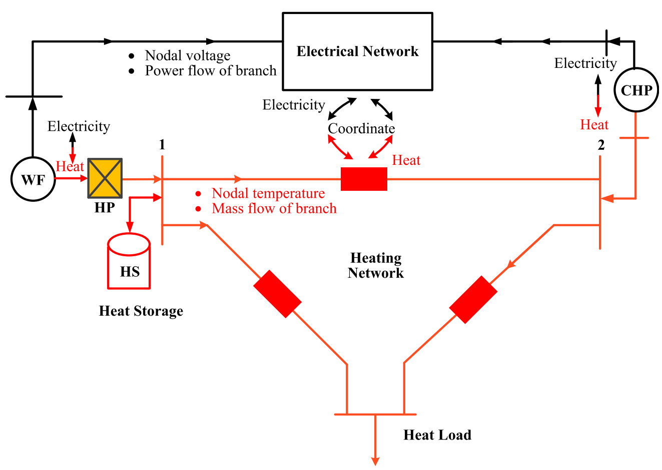
Jinghua Li [a,b,*], Jiakun Fang [b], Qing Zeng [b], Zhe Chen [b]

[a] College of Electrical Engineering, Guangxi University, Nanning 530004, China
[b] Department of Energy Technology, Aalborg University, Aalborg DK9220, Denmark

## HIGHLIGHTS

- The optimization problem of combing electricity and heat is formulated.
- An efficient algorithm is studied for solving the integrated problem.
- The amount of the energy conversion between electricity and heat is decided.
- The best node to join with the electrical system and heating system is chosen.
- Benefits of the integration of electricity and heat are discussed.

## GRAPHICAL ABSTRACT




## ARTICLE INFO

*Article history:*
Received 29 May 2015
Received in revised form 6 October 2015
Accepted 7 October 2015
Available online xxxx

*Keywords:*
Integrated energy system
Combined electricity and heat
Intermittent renewable sources
Optimal operation of energy system
Decomposition–coordination algorithm

## ABSTRACT

The integration of electrical and heating systems has great potential to enhance the flexibility of power systems to accommodate more renewable power such as the wind and solar. This study was to investigate an optimal way to integrate the energy of both systems in urban areas. The amount of energy conversion between the electrical system and heating system was optimally decided so that the demand within both systems could be met at the least operational cost. Besides, the best node to join with the electrical system and heating system was chosen by consideration of the energy transmission loss. The mathematical formulation of the optimization problem was detailed as a large-scale non-linear program (LSNLP) in this paper. A decomposition–coordination algorithm was proposed to solve this LSNLP. At last, a 6-bus electrical power system with 31-node heating transmission system was studied to demonstrate the effectiveness of the proposed solution. The results showed that coordinated optimization of the energy distribution have significant benefits for reducing wind curtailment, operation cost, and energy losses. The proposed model and methodology could help system operators with decision support in the emerging integrated energy systems.



* Corresponding author at: College of Electrical Engineering, Guangxi University, Nanning 530004, China.
*E-mail address:* happyjinghua@163.com (J. Li).

http://dx.doi.org/10.1016/j.apenergy.2015.10.054
0306-2619/© 2015 Elsevier Ltd. All rights reserved.

**Nomenclature**

Heating system

*Indices*

$T$ heat system

CHP, HS, HP combined heat and power plant, heat storage, heat pump

*Parameters*

$B^{T}_{num}$, $N^{T}_{num}$ number of branches and nodes

$S^{Heat}_{num}$, $S^{CHP}_{num}$, $S^{HP}_{num}$, $S^{HS}_{num}$ number of heat sources, CHP, HP, and HS

$A, B$ incidence matrix, circuit matrix

$\alpha$ cost coefficient of thermal power

$c$ the specific heat capacity of water

$\gamma, l$ heat loss coefficient of the branch, length of the branch

$R_1, R_2$ resistance of channel and insulation material (m °C/W)

$\beta$ additional heat loss coefficient of pipe auxiliaries, valve, and compensator

$L$ heat load of node (kW)

$BQ^{min}$, $BQ^{max}$ minimum, maximum mass flow rate of branch (t/h)

$SP^{HP,min}$, $SP^{HP,max}$ minimum, maximum thermal power of HP (kW)

$SP^{CHP,min}$, $SP^{CHP,max}$ minimum, maximum thermal power of CHP (kW)

$SP^{HS,min}$, $SP^{HS,max}$ minimum, maximum thermal power of HS (kW)

$t^{Back}$, $t^{min}$, $t^{max}$, $t_0$ temperature of return water, minimum and maximum temperature of node, ambient environment temperature (°C)

$SQ^{HS,max}$, $SQ^{HS}_{0}$ the capacity of HS (MW h), initial heat of HS (MW h)

$K^{e}, \eta^{l}, \eta^{e}$ heating coefficient of bromine refrigerator, heat loss coefficient and generated coefficient of CHP

*Variables*

BQ mass flow rate of branch (t/h)

NQ mass flow rate of nodal load (t/h)

$e$ temperature drop coefficient of branch (°C/(t/h))

$\Delta t, t$ temperature drop of branch, temperature (°C)

$SQ = [SQ^{HP}; SQ^{CHP}; SQ^{HS}]$ mass flow rate of HP, CHP, HS (t/h)

$SP = [SP^{HP}; SP^{CHP}; SP^{HS}]$ thermal power of HP, CHP, HS (kW)

$d^{ch}, d^{dis}$ charging and discharging state of HS

Electrical system

*Indices*

$E$ electrical system

G, Q, CHP, W traditional thermal generator, reactive power source, combined heat and power plant, wind power

*Parameters*

$B^{E}_{num}$, $N^{E}_{num}$ number of branches and nodes

$S_{num}$ number of power sources

$P^{ramp}$ maximum power of the generator ramping up or down during a time interval

$P^{min}$; $P^{max}$ minimum, maximum output of active power sources

$Q^{min}$, $Q^{max}$ minimum, maximum output of reactive power sources

$U^{min}$, $U^{max}$ minimum, maximum limits of nodal voltage

$P^{min}_{i'j'}$, $P^{max}_{i'j'}$ minimum, maximum limits of line's transmission power

$P^{W,av}$ the available wind power of wind farm

$\eta_{W-T}$ the conversion efficiency from wind power to heat

$a_0, a_1, a_2$ the cost coefficients of $G$

*Variables*

$U, \theta$ magnitude of voltage, angle of voltage

$P, Q$ active power, reactive power

$P^{W,cur}$ wind curtailment before converting to heat

$\tilde{P}^{W,cur}$ wind curtailment after converting to heat

## 1. Introduction

The climate change, fossil resource depletion, policy incentives as well as higher public awareness in term of sustainability have promoted the deployment of renewable generations, typically wind power and photovoltaic [1]. However, the intermittent and unpredictable features of the renewable generations raise the challenge to the power system operators to balance energy production and consumption. To accommodate the continuously increasing renewable sources connected to the grids, there is an urgent need to either enhance the system flexibility or mitigate the variability. Traditionally, when being operated independently, the power systems can acquire flexibility only through those fast-ramping generators [2,3], power flow regulations, electrical energy storages [4], and manageable loads [5,6]. Alternatively, the coordination single or multiple renewable sources in a certain region has been proved to be an effective way to mitigate the renewable's variability [7–9]. And together with a better energy management strategy the requirements to the system flexibility could be further reduced while with the energy adequacy guaranteed [10].

In recent years, the emerging technologies enhanced the interdependency of different energy systems. Research investigations and industrial practices have demonstrated the integrated energy systems (IES) could coordinate energy production and consumption in a broader scope, and hence improve the overall efficiency and sustainability of the energy utilization [11]. The integrated energy system consists of the electrical system, natural gas system, district heating system and electrified transportation system. The electrified vehicle can act as both a manageable load [12] and an energy carrier [13] to support the energy system operation. The power-to-gas plants, together with the gas-fired turbines can improve the dispatching ability of the renewable generations via temporal and spatial shifting [14]. The energy in the district heating systems may come from electrical heat pumps, solar power and co-generation of electricity, all of which are associated with electrical systems, and hence draws broad interests.

Extensive work has been done in optimal integration of electrical and heating systems. At the device level, the thermoelectric generators have been well modeled and optimized via both theoretical and experimental studies [15,16]. Some of the work focuses on providing reliable and sustainable electricity and heat to the residential demands such as buildings and communities [17,18]. In [19], a mixed-integer linear programming model has been developed for the integrated plan and evaluation of distributed energy systems. The analogy between the electrical circuit and heat transfer networks has been studied in [20]. At the macro level, computer tools have been developed to simulate and analyze the future integrated energy systems [21]. Taking Energy Plan [22] for example, it has been used in various regions for decision support on their development strategies [23]. However, the topologies of the heat and electrical networks are usually neglected for brevity.