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An optimization method for multi-area combined heat and power production with power transmission network

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HIGHLIGHTS

- Decomposition-based optimization method for CHP production and power transmission problems.
- Minimization of CHP production cost to meet the local heat demand and identify the optimal power transmission between areas.
- Solving a small sample problem using the developed models to show the solution approach.
- Method allows using fast specialized algorithms to solve the sub-problems of multiple areas.
- Fast solution of hourly problems is useful in solving long-term problems.

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ABSTRACT

This paper presents an efficient decomposition-based optimization method to optimize the hourly combined heat and power (CHP) production and power transmission between multiple areas. The combined production and power transmission problem is decomposed into local CHP production models and into a power transmission model. The CHP production models are formulated as linear programming (LP) models and solved using a parametric analysis technique to determine the local production cost as a function of power transmitted into or out from each area. To obtain the overall optimum, the power transmission problem is then formulated in terms of the parametric curves as a network flow problem, and solved using a special network Simplex algorithm. The decomposition method has been tested with different sized artificial problems. The method can be used in situations where it is necessary to solve a large number of hourly production and transmission problems efficiently. As an example, the method can be used as part of long-term planning and simulation of CHP systems in different cities or countries connected by a common power market.

1. Introduction

Combined heat and power (CHP) is the most efficient way to deliver power, heating and cooling [1]. Based on some statistic data for 2012, CHP electricity generation for the 28 member states of the EU was 373.3 TW h, and heat production was 854.5 TW h [2]. The importance of CHP in district heating system also has been pointed out [3,4]. In Finland, the share of CHP electricity was about 34% and district heating 74% in 2014 [5]. CHP can utilize different types of fuels such as waste, biomass and also traditional fossil fuels [6,7]. Through the heat utilization, efficiency of CHP can be more than 90% and therefore offers dramatic savings of energy ranging between 15% and 40% in comparison with conventional power plants and heat only boilers [1]. Environmental benefits of CHP in comparison with other conventional plants are due to reduction in emissions [8]. The role of CHP was investigated in a study based on zero emissions scenario [9]. In 2014, the European Commission presented a new framework for climate and energy policy for 2030. Its targets comprise increasing renewable energy utilization, improving energy efficiency, and reducing greenhouse emissions. The targets depend on economic analysis measuring how to achieve decarburization cost-effectively by 2050 [10].

The optimal operation of local CHP production can be determined by an optimization model. The objective is to minimize the total cost of energy production while satisfying demand and operational constraints. The complexity arises from the coupling of power and heat production to match both heat and power demand. The problem will be more complicated, when power transmission between multiple areas is also considered. As a result, faster methods and solvers are needed for optimizing for large scale energy production problems.

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Nomenclature

Abbreviations

CHP	combined heat and power
LP	linear programming
NP2	efficient network simplex algorithm
CHPED	combined heat and power economic dispatch
MILP	mixed integer linear programming
CPU time	central processing unit time (s)

Symbols

A	set of arcs
$\mathbf{b}$	additional constraints coupling heat and power production (MW h)
C	cost (€)
c_a	transmission cost (€/MW h)
c_j, p_j, q_j	production cost (€), power generation (MW h), and heat production (MW h) at characteristic point j
c_{cond}	condensing power price (€/MW h)
c_{hob}	heat only boiler price (€/MW h)
c^l	marginal cost of production (slope of line segment) (€/MW h)
d_i	demand in node i (MW h)
$dest(a)$	destination node of arc a
$\mathbf{H}$	matric for heat and power production (MW h)
J	set of extreme characteristic points of all CHP plants in a production area
J_u	set of extreme characteristic points for CHP plant $u \in U$
m	number of production arcs
N	set of the nodes (production areas)
n	number of areas
$org(a)$	origin node of arc a
P	power demand (MW h)
Q	heat demand (MW h)
U	set of CHP plants
u_a	transmission line capacity (MW h)
$\mathbf{x}$	decision variable to encode convex combination
x_j	variables used to encode convex combination of operating region
x_{hob}	heat production of heat only boiler (MW h)
x_{cond}	power production of condensing power plant (MW h)
x_{hob}^{max}	maximum capacity for heat only boiler production (MW h)
x_{cond}^{max}	maximum capacity condensing power plant production (MW h)
y	power transmission (MW h)
y_a	power flowing from origin node to destination node (MW h)

Superscripts and subscripts

a	arc (transmission line between areas)
$cond$	condensing power plant production
hob	heat only boiler production
i, k	indices for nodes (production areas) in network
l	line segment index
p, q	power and heat products
$prod$	production
$trans$	transmission

The complexity of optimization problems depends strongly on the shape of the objective function and constraints. For example, minimization of convex objective function subject to convex constraints is in general easier than solving non-convex problems. Several models for convex and non-convex problems have been developed to solve combined heat and power economic dispatch (CHPED) problems. For convex CHPED problems, linear models have been proposed and solved by using specialized Simplex algorithms [11–13]. Non-convex CHPED problems may arise from a non-convex characteristic operating region or the need to optimize unit commitment (when to shut down and start up plants). A non-convex CHPED operating region can be divided into convex subregions and formulated as a mixed integer linear programming (MILP) model, or solved using the Lagrangian relaxation technique [14–18]. To determine the unit commitment of CHP plants, a unit decommitment algorithm was developed and the solution quality was compared with a generic unit decommitment algorithm by using realistic test data [14]. Reference [19] presents a thorough comparison of 37 software tools for different energy applications, ranging from single building models to national energy systems. In particular, the study evaluated the suitability of the tools for integrating renewables into energy systems. Six of the tools were applicable for modeling CHP plants. The BCHP Screening Tool analyzes the combined heating, cooling, and power systems of commercial buildings, excluding large scale heat, power or transport sectors [20]. COMPOSE and EnergyPRO can be used for techno-economic analysis of single projects [21,22]. BALMOREL can simulate the CHP sector in a multi-national geographical area [23]. EnergyPLAN and SIVAL are tools for national or regional energy systems [24,25]. Among them only EnergyPRO and EnergyPLAN can simulate 100% renewable energy systems. They have been used to verify the results of linear programming (LP) models for renewable energy systems with energy storages [26–28]. Table 1 presents an overview of different scale energy systems, which have been solved using different algorithms.

A review over research on the CHPED problem was presented in [33]. The high efficiency and profitability of CHP production can be further improved by utilization of power transmission network. Accurate modeling of energy production together with power transmission network in a large scale problem requires a sophisticated optimization model. Efficient solution of CHPED problems is important because a long-term planning model includes thousands of hourly models, and rapid re-optimization is needed when the market situation changes.

In this paper, the hourly multi-area CHP production and power transmission problem is formulated as an LP model, but decomposed and solved as separate local CHP production models and an overall model for the power transmission problem. In the local CHP problems, the produced power can be sold to the grid at market price, but heat must be produced to meet the local demand for district heating or specific industrial processes. The local CHP production is modeled as LP problems and solved using a special parametric LP algorithm. This will yield the local production costs as a function of the power production. Then the local production cost curves are encoded as a network flow problem into an overall production and power transmission problem. A specialized primal network simplex algorithm NP2 is used to solve the network flow model. The overall optimization model minimizes the combined production costs in all areas and identifies the optimal balance between local production and power transmissions into or out from each area. The solution technique should be fast enough to solve even large hourly optimization problems with many CHP