Optimal dispatch of combined heat and power plant in integrated energy system: A state of the art review and case study of Copenhagen

Wang, Jiawei; You, Shi; Zong, Yi; Træholt, Chresten; Zhou, You; Mu, Shujun

Published in:
Energy Procedia

Link to article, DOI:
10.1016/j.egypro.2019.02.040

Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.
Optimal dispatch of combined heat and power plant in integrated energy system: A state of the art review and case study of Copenhagen

Jiawei Wang\textsuperscript{a}, Shi You\textsuperscript{a,*}, Yi Zong\textsuperscript{a}, Chresten Træholt\textsuperscript{a}, You Zhou\textsuperscript{b}, Shujun Mu\textsuperscript{b}

\textsuperscript{a}Technical University of Denmark, 2800 Kgs. Lyngby, Denmark
\textsuperscript{b}National Institute of Clean and Low Carbon Energy, 102211 Beijing, China

Abstract

This paper presents and classifies a state of the art optimal dispatch review of combined heat and power plants (CHP) in integrated energy systems. Comparing the purposes of increasing renewable energy integration and profits of CHP operation, two groups of literatures, cost and market based optimal dispatch of CHP plants are studied. The flexibility in terms of reducing wind power curtailment and increasing revenue by providing ancillary service is discussed. A case study of optimal dispatch of a CHP plant under the heat market in Copenhagen, Denmark is proposed, where the flexibility is compared with different CHP unit types, operation modes and heat accumulators’ integration.

© 2019 The Authors. Published by Elsevier Ltd.
This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)
Peer-review under responsibility of the scientific committee of ICAE2018 – The 10th International Conference on Applied Energy.

Keywords: Combined heat and power; flexibility; integrated energy system; optimal dispatch

1. Introduction

With the high penetration of renewable energy, a future integrated energy system (IES) is proposed to achieve an optimal solution for each energy sector and the whole system [1]. A potential solution of 100% renewable energy system in Europe by 2050 can be achieved by integrating all energy sectors with each other [2]. Combined heat and power (CHP) is a key technology connecting electric power and heating sectors for its high total power and heat generation efficiency. In Denmark, CHP plants cover around 60% of Danish district heating (DH) supply and more than 50% of Danish electricity generation in 2016 [3-4]. The optimal dispatch of CHP plants is a short term operational planning to determine the heat and power output, usually hourly-based, by achieving optimal technical

\* Corresponding author.
\textit{E-mail address: sy@elektro.dtu.dk}
2. A state-of-the-art review of CHP plants' optimal dispatch in IES

The literature review is classified into two groups: relevant literature on optimal dispatch of CHP plants regardless of revenue from energy market and considering the revenue from different markets.

2.1. Literature on cost based optimal dispatch of CHP plants

Regardless of revenue from energy market, the objective is based on system operation cost and technical requirements. Table 1 categorizes the standout literature within this group including key characteristics. The objective function together with the constraints determines the optimization method of linear programming (LP), mixed integer linear programming (MILP) and nonlinear programming (NLP).

Among the developed researches, Dai et al. [13] consider the heat transfer process of heat exchanger connecting CHP plant and DH network. Flexibility of heat transfer process is explored to reduce the wind power curtailment. The limited flexibility of CHP units can be improved by utilizing HA, normally a hot water based vessels located in the CHP plant and connected to DH system [14]. Chen et al. [15] investigate the extended flexibility of CHP plants through EB and HA. Chen et al. [16] stand out for the convexity of non-convex extraction modeling of CHP units and investigation of dynamic constraints of ramp rate and minimum on/off time of CHP operation. Li et al. [17] and Lin et al. [18] explore the flexibility for managing the wind power curtailment through the energy storage capacity inside the DH pipeline. A node method is implemented to model its temperature dynamics which act as an energy buffer between CHP plant and heat load [17]. A decentralized solution based on Benders decomposition is proposed for optimal dispatch by operators of power system and DH iteratively [18]. Ommen et al. [20] highlight its research by comparing LP, NLP and MILP model of CHP units based on real case in Copenhagen, Denmark. The MILP caused by minimum load requirement and NLP caused by partial load efficiency of boiler lead to a higher operation time of HPs. Additionally, rolling horizon (RH) method is implemented to update the forecast of heat demand and electricity price, which can reduce the forecast error and computation time. Liu et al. [21] develop an integrated electrical-hydraulic-thermal calculation technique to solve the nonlinear model of energy flow in the network through Newton-Raphson method. The proposed technique is implemented in a real case of the Barry Island and validated by commercial software. Li et al. [22] propose an optimization technique of decomposition-coordination algorithm to solve the large-scale nonlinear optimization.

2.2. Literature on market based optimal dispatch of CHP plants

The dispatch of CHP units is always together with other heat generation units based on marginal heat cost, where
the electricity revenue from power market is deducted [23]-[25]. The increasing revenue of CHP plants can be obtained by joining in the intraday and ancillary service market, which provides frequency regulation and balancing power in real time. Table 2 collects the standout literature within this group including key characteristics.

Ommen et al. [26] investigate the optimal dispatch of the system considering electricity trade with neighboring network. Mollenhauer et al. [27] investigate the flexibility by HA and HP to reduce the marginal heat cost by taking advantage of fluctuating electricity price. HA enables the CHP unit to shift its power generation from low to high electricity price period. HP benefits the economic operation of CHP units with lower flexibility more, e.g. backpressure CHP units. Fang and Lahdelma [28] implement the RH method to update the heat demand and Elspot price forecast which can save 90% of system cost derived based on perfect forecast. Rong et al. [29] propose a bi-objective optimal dispatch by simultaneously minimizing the heat cost and the emission cost. Mitridati and Pinson [30] investigate a stochastic hierarchical formulation of joint heat and power dispatch, where the heat cost optimization considering the uncertainty of Elspot price and day-ahead electricity market clearing considering the power limit by heat dispatch are performed sequentially. Rolfsman [31] optimizes the dispatch of CHP units considering the schedule adjustment in balancing market due to the forecast error of Elspot price in day-ahead market. Hellmers et al. [32] propose two sequential optimization problems, which maximize profit of day-ahead operation in heat and electricity market and minimize the net cost including revenue from balancing market. Results show that the portfolio operation of CHP unit and wind power plant in balancing market is more profitable than individual operation. Kumbartzky et al. [33] propose a MILP model that simultaneously optimizes the operation of CHP with HA and bidding in sequential electricity market. Zugno et al. [34] investigate a two-stage affinely

<table>
<thead>
<tr>
<th>Key characteristics</th>
<th>[13]</th>
<th>[15]</th>
<th>[16]</th>
<th>[17]</th>
<th>[18]</th>
<th>[19]</th>
<th>[20]</th>
<th>[21]</th>
<th>[22]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective function</td>
<td>Fuel cost/consumption</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Startup and shutdown cost</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Penalty cost on energy imbalance</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CHP model</td>
<td>Convex combination</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Energy efficiency</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heat transfer process</td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dynamic limit</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy flow in network</td>
<td>Power system</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Heating system</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Flexibility provider</td>
<td>HA</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>EH</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DH pipeline</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Heat exchanger</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Optimization method</td>
<td>LP</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>MILP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>NLP</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RH</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Key characteristics</th>
<th>[26]</th>
<th>[27]</th>
<th>[28]</th>
<th>[29]</th>
<th>[30]</th>
<th>[31]</th>
<th>[32]</th>
<th>[33]</th>
<th>[34]</th>
<th>[35]</th>
<th>[36]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective function</td>
<td>Operation cost</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Emission cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity Market</td>
<td>Day-ahead market</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Intraday market</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ancillary service type</td>
<td>Balancing power</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Flexibility provider</td>
<td>HA</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>EH</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>CHP unit type</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optimization method</td>
<td>Mono-objective</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Multi-objectives</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stochastic</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RH</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>
adjustable robust optimization for optimal heat and power dispatch with MILP. Stochastic variables of heat demand and electricity price, and real-time adjustment in balancing market are considered. Sorknæs et al. [35] implement daily optimal dispatch considering revenue from balancing service with commercial software energyPRO and a real case in western Denmark is studied. Haakana et al. [36] investigate the CHP optimal operation sequentially in electricity market of day-ahead, frequency containment reserve (FCR) and intraday market.

3. Case study of optimal dispatch of CHP plants within Copenhagen heat market

In this section, a case study of joint heat and power dispatch of a CHP plant based on Copenhagen heat market is proposed. The developed CHP unit models are based on real parameters of Copenhagen CHP plant [26][37]. Scaled and shifted heat load profile of a commercial building is tested and the flexibility provided by different CHP units and HA are studied. The system configuration, heat load profile and Elspot price are shown in Fig.1. Heat generation by the CHP unit $Q_{i}^{CHP}$ and HA $Q_{i}^{HA}$ supply the heat load $Q_{i}^{LD}$. The power generation from the CHP unit $P_{i}^{CHP}$ is exported to the electric network and assumed to be accepted by the day-ahead electricity market.

3.1. Optimal heat and power dispatch under Copenhagen heat market

Under the current heat market regulation of Copenhagen [24], the hourly optimal dispatch of the CHP plant is formulated as below.

$$\min \sum_{i,t} (C_{i,t}^{CHP} + C_{i,t}^{HA} - R_{i,t}^{ele} + C_{i,t}^{bipen})$$

(1)

$$C_{i,t}^{CHP} = (c_{i,t}^{fuel} + c_{i,t}^{tax} + c_{i,t}^{CO2}) \times F_{i,t}^{CHP} + c_{i,t}^{CHP} \times (P_{i,t}^{CHP} + Q_{i,t}^{CHP}), C_{i,t}^{HA} = c_{i,t}^{HA} \times Q_{i,t}^{HA}.$$  

(2)

where the objective is to minimize the total marginal heat cost including the variable cost of CHP unit $C_{i,t}^{CHP}$ and HA $C_{i,t}^{HA}$, predicted revenue from day-ahead electricity market $R_{i,t}^{ele}$ and penalty on excess or deficit heat generation $C_{i,t}^{bipen}$ during the schedule period of $T$. The cost factor of fuel cost, operation and maintenance (O&M) cost, CO2 quota and fuel tax are represented by $c_{i,t}^{fuel}$, $c_{i,t}^{CHP}$, $c_{i,t}^{CO2}$ and $c_{i,t}^{tax}$ [38]. $P_{i,t}^{CHP}$, $Q_{i,t}^{CHP}$ and $F_{i,t}^{CHP}$ correspond to the power and heat generation and fuel consumption. The electricity revenue includes Elspot price $c_{i,t}^{ele}$ and subsidy of biomass $c_{i,t}^{sub}$. Other constraints of CHP and HA modeling, ramp rate limit are not expressed but referred to [26][16]. Five types of CHP units: backpressure, backpressure with partial efficiency with and without bypass operation, mode enables its operation with lower heat cost compared with backpressure CHP units. In winter time, the flexibility of bypass operation leads to a lower heat cost compared with nonlinear backpressure without bypass operation. The flexibility provided by HA benefits the system economic operation in winter for all CHP units and for backpressure CHP units in summer. The heat and power decoupling by HA enables the heat production shift according to the Elspot price variation, therefore a more flexible operation. For exaction CHP units operation in summer, the flexibility itself is enough for an economic operation therefore HA increases the cost for its heat loss.

3.2. Results and analysis

Case studies of the commercial heat load during two weeks in summer and winter are proposed. Hourly optimal joint power and heat dispatch for each week is executed. Fig.2 shows the total marginal heat cost of the five CHP units during two weeks with and without HA. In summer time, the flexibility of extraction CHP units in condensing mode enables its operation with lower heat cost compared with backpressure CHP units. In winter time, the flexibility of bypass operation leads to a lower heat cost compared with nonlinear backpressure without bypass operation. The flexibility provided by HA benefits the system economic operation in winter for all CHP units and for backpressure CHP units in summer. The heat and power decoupling by HA enables the heat production shift according to the Elspot price variation, therefore a more flexible operation. For exaction CHP units operation in summer, the flexibility itself is enough for an economic operation therefore HA increases the cost for its heat loss.

4. Conclusion

This paper presents a literature review of the optimal dispatch of CHP plants in IES which is grouped into cost
based and market based operation. Different classifications of objective function, CHP model, flexibility provider, ancillary service market and optimization methods are proposed and compared. It shows a trend that more flexible operation of CHP units for technical purpose like more renewable energy integration can be realized by being dispatch together with HA, EB and HP. A more profitable operation of CHP units can be obtained by participating in multiple markets, by providing ancillary services like frequency regulation and real-time power balancing. A case study based on real case of a CHP plant and heat market in Copenhagen Denmark is evaluated. Results show the flexibility evaluated by the total heat cost varies from different CHP types, CHP operation modes, HA integration and seasonal load profiles. A framework of optimal dispatch of CHP units considering providing flexibility to the IES in order to enhance the renewable energy integration and provide ancillary services to the grid will be studied in the future work. Optimal dispatch of CHP units and EH within the new tax regulation of heat market and within electricity market will be proposed.

Acknowledgements

This work is supported by “EnergyLab Nordhavn-New Urban Energy Infrastructures and Smart Components” project grant by the EUDP (Energy Technology Development and Demonstration Programme) (No. 64015-0055) and “Enhancing wind power integration through optimal use of cross-sectoral flexibility in an integrated multi-energy system (EPIMES)” Sino-Danish project granted by the Danish Innovation Funding (No. 5185-00005B).

References

IES in order to enhance the renewable energy integration and provide ancillary services to the grid will be studied in and seasonal load profiles. A framework of optimal dispatch of CHP units considering providing flexibility to the flexibility evaluated by the total heat cost varies from different CHP types, CHP operation modes, HA integration [1]

References

Acknowledgements

This work is supported by "EnergyLab Nordhavn-New Urban Energy Infrastructures and Smart Components"


Sino-Danish project granted by the Danish Innovation Funding (No. 5185-00005B).


