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

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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.

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

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and economic goals [5]. The static and dynamic constraints of system operation are often considered during the dispatch. The technical goals usually focus on increasing the integration of renewable energy. This requires a more flexible operation of conventional generation units which run as base load, e.g. CHP plants [6]. The flexibility of a CHP plant in the context of accommodating variable and uncertain renewable energy depends partly on its unit types, operation modes (condensing, extraction and backpressure), ramp rate and start up time [7]. The flexibility can be improved by adding heat accumulators (HA), electrical heating (EH) (including electric boilers (EB) and heat pumps (HP)) and a bypass operation option of power generation [8].

Additionally, CHP plants are confronted with decreasing profits. Since the variable cost of renewable energy is rather low, its high integration can cause low electricity price and few operation hours of CHP plants. In Denmark, compared with 2010, the annual electricity generation from CHP plant is reduced by 58% in 2016 [9]. In addition, the cogeneration characteristics of CHP plants restrict its power generation by heat generation. This limit comes from technical constraints of power to heat ratios under different operation modes. Also the trade of power and heat is responsible by separate market operators [10], and their wholesale prices are quite different [11][12]. Therefore, the optimal dispatch of CHP plants ensures a low cost operation and explores more revenue from different markets.

The remainder of the paper is organized as follows: a review of literature on optimal dispatch of CHP plants in IES is introduced in section 2. A case study of optimal dispatch of a real case of a CHP plant within Copenhagen heat market is proposed in section 3. The conclusion and future work are discussed in section 4.

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 1. Literature on cost based optimal dispatch of CHP plants.

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

Table 2. Literature on market based optimal dispatch of CHP plants.

Key characteristics		[26]	[27]	[28]	[29]	[30]	[31]	[32]	[33]	[34]	[35]	[36]
Objective function	Operation cost	x	x	x	x	x	x	x	x	x	x	x
	Emission cost				x							
	Revenue from heat market							x				x
Electricity Market	Day-ahead market	x	x	x	x	x	x	x	x	x	x	x
	Intraday market											x
	Ancillary service market						x	x	x	x	x	x
Ancillary service type	Balancing power						x	x	x	x	x	
	FCR											x
Flexibility provider	HA	x	x	x			x	x	x	x	x	
	EH	x	x								x	
	CHP unit type		x							x		x
Optimization method	Mono-objective	x	x	x			x				x	x
	Multi-objectives				x	x		x	x	x		
	Stochastic					x			x	x		
	RH			x				x				

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^{HA} supply the heat load Q^{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.

$$\min \sum_{t\in T}(C_{i,t}^{CHP} + C_t^{HA} - R_t^{ele} + C_t^{htpen}) \quad (1)$$

$$\begin{gathered} C_{i,t}^{CHP} = (c^{fuel} + c^{tax} + c^{CO_2}) \times F_{i,t}^{CHP} + c_{O\&M}^{CHP} \times (P_{i,t}^{CHP} + Q_{i,t}^{CHP}), C_t^{HA} = c_{O\&M}^{HA} \times \left|Q_t^{HA}\right|, \\ R_t^{ele} = (c_t^{ele} + c^{sub}) \times P_{i,t}^{CHP}, C_t^{htpen} = c^{ex} \times Q_t^{ex} + c^{def} \times Q_t^{def}, i \in I, t \in T \end{gathered} \quad (2)$$

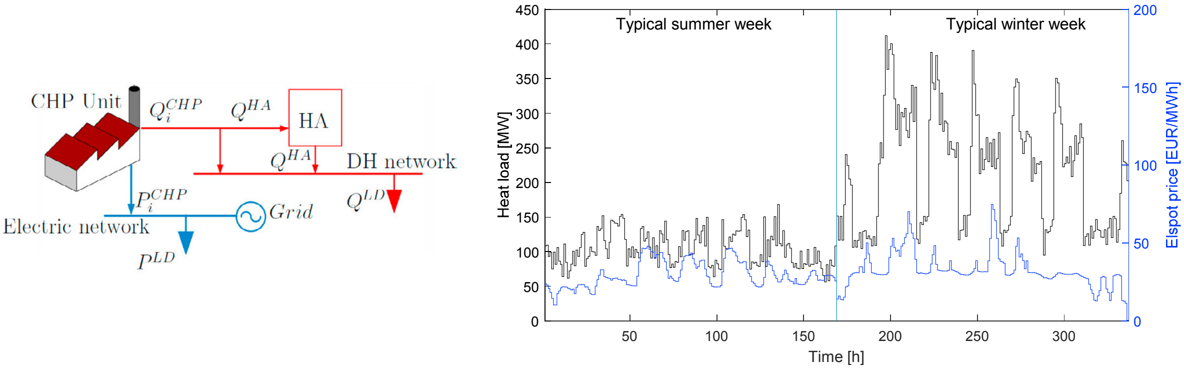
where the objective is to minimize the total marginal heat cost including the variable cost of CHP unit $C_{i,t}^{CHP}$ and HA C_t^{HA}, predicted revenue from day-ahead electricity market R_t^{ele} and penalty on excess or deficit heat generation C_t^{htpen} during the schedule period of T. The cost factor of fuel cost, operation and maintenance (O&M) cost, CO_2 quota and fuel tax are represented by c^{fuel}, $c_{O\&M}^{CHP}$, c^{CO_2} and c^{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_t^{ele} and subsidy of biomass c^{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, extraction with one and two power loss factors are implemented. In order to make the results comparable, the maximum and minimum boiler capacity, efficiency of full load operation and ramp rate of CHP units are the same.

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.

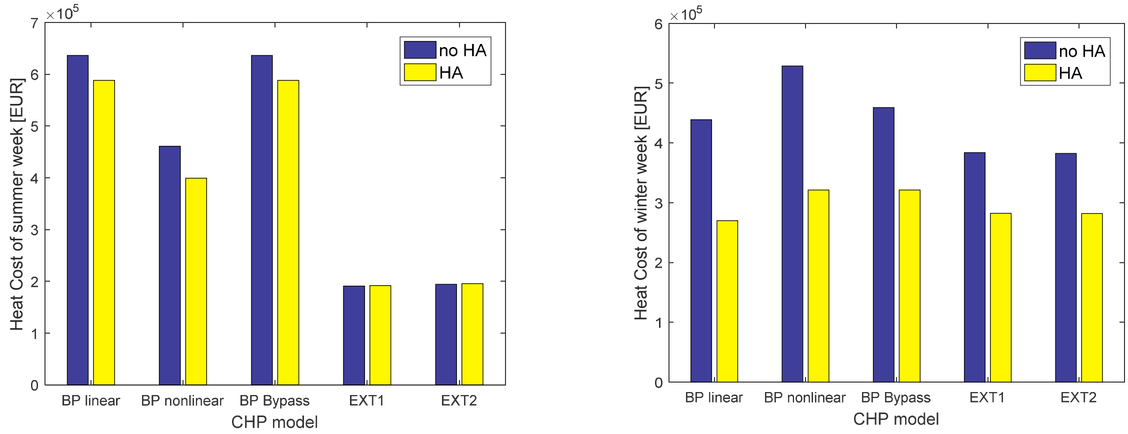
4. Conclusion

This paper presents a literature review of the optimal dispatch of CHP plants in IES which is grouped into cost



(a) (b)

Fig. 1. (a) CHP plant in IES system (b) heat load profile and Elspot price



(a) (b)

Fig. 2. Total heat cost during the (a) summer week (b) winter week

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.

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References

[1] Lund H, Østergaard PA, Connolly D, Mathiesen BV. Smart energy and smart energy systems. Energy 2017 Oct;137:556–65.

[2] Connolly D, Lund H, Mathiesen BV. Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renew Sustain Energy Rev 2016 Jul;60:1634–53.
[3] Pedersen BR. District heating in Denmark. [Presentation]. Danish Energy Agency, 20th Jun. 2017.
[4] Energinet. Environmental report for Danish electricity and CHP for 2016 status year. Denmark. Report. no.: 16/19207-5, 2017.
[5] Salgado F, Pedrero P. Short-term operation planning on cogeneration systems: A survey. Electr Power Syst Res 2008 May;78(5):835–48.
[6] Agora Energiewende. Flexibility in thermal power plants – with a focus on existing coal-fired power plants. Jun. 2017.
[7] Danish Energy Agency. Technology data for Energy plants. Nov. 2017.
[8] Bæk M. Regulation and planning of district heating in Denmark. Danish Energy Agency. Dec. 2015.
[9] Wang J, Zong Y, You S, Træholt C. A review of Danish integrated multi-energy system flexibility options for high wind power penetration. Clean Energy. 2017;1(1):23-35.
[10] Pinson P, Mitridati L, Ordoudis C, Ostergaard J. Towards fully renewable energy systems: Experience and trends in Denmark. CSEE J Power Energy Syst 2017 Mar 20;3(1):26–35.
[11] Yang X, Li H, Svendsen S. Evaluations of different domestic hot water preparing methods with ultra-low-temperature district heating. Energy 2016 Aug;109:248–59.
[12] Day-ahead prices. Available at: https://www.nordpoolgroup.com/Market-data1/Dayahead/Area-Prices/ALL1/Hourly/?view=table.
[13] Dai Y, Chen L, Min Y, Chen Q, Hu K, Hao J, et al. Dispatch Model of Combined Heat and Power Plant Considering Heat Transfer Process. IEEE Trans Sustain Energy 2017 Jul;8(3):1225–36.
[14] Haga N, Kortela V, Ahnger A. Smart power geneartion – district heating solutions. Wärtsilä. 2012.
[15] Chen X, Kang C, O'Malley M, Xia Q, Bai J, Liu C, et al. Increasing the Flexibility of Combined Heat and Power for Wind Power Integration in China: Modeling and Implications. IEEE Trans Power Syst 2015 Jul;30(4):1848–57.
[16] Chen X, McElroy MB, Kang C. Integrated Energy Systems for Higher Wind Penetration in China: Formulation, Implementation and Impacts. IEEE Trans Power Syst 2017;8950(c):1–12.
[17] Li Z, Wu W, Shahidehpour M, Wang J, Zhang B. Combined Heat and Power Dispatch Considering Pipeline Energy Storage of District Heating Network. IEEE Trans Sustain Energy 2016 Jan;7(1):12–22.
[18] Lin C, Wu W, Zhang B, Sun Y. Decentralized Solution for Combined Heat and Power Dispatch through Benders Decomposition. IEEE Trans Sustain Energy 2017;3029(c):1–1.
[19] Dimoulkas I, Amelin M, Levihn F. District heating system operation in power systems with high share of wind power. J Mod Power Syst Clean Energy 2017 Nov 22;5(6):850–62.
[20] Ommen T, Markussen WB, Elmegaard B. Comparison of linear, mixed integer and non-linear programming methods in energy system dispatch modelling. Energy. 2014;74(1):109–18.
[21] Liu X, Wu J, Jenkins N, Bagdanavicius A. Combined analysis of electricity and heat networks. Appl Energy 2016 Jan;162:1238–50.
[22] Li J, Fang J, Zeng Q, Chen Z. Optimal operation of the integrated electrical and heating systems to accommodate the intermittent renewable sources. Appl Energy 2016;167:244–54.
[23] Sjödin J, Henning D. Calculating the marginal costs of a district-heating utility. Appl Energy. 2004;78(1):1–18.
[24] Heating plans. Available at: http://www.varmelast.dk/en/heat-plans/heating-plans.
[25] Jensen F. Modeling of the combined heat and power systems of Greater Copenhagen. Master thesis. Technical University of Denmark. 2010
[26] Ommen T, Markussen WB, Elmegaard B. Lowering district heating temperatures--Impact to system performance in current and future Danish energy scenarios. Energy. 2016;94:273–91.
[27] Mollenhauer E, Christidis A, Tsatsaronis G. Increasing the Flexibility of Combined Heat and Power Plants With Heat Pumps and Thermal Energy Storage. J Energy Resour Technol 2017 Nov 30;140(2):20907.
[28] Fang T, Lahdelma R. Optimization of combined heat and power production with heat storage based on sliding time window method. Appl Energy 2016;162:723–32.
[29] Rong A, Figueira JR, Lahdelma R. A two phase approach for the bi-objective non-convex combined heat and power production planning problem. Eur J Oper Res 2015 Aug;245(1):296–308.
[30] Mitridati L, Pinson P. Optimal coupling of heat and electricity systems: A stochastic hierarchical approach. In: 2016 International Conference on Probabilistic Methods Applied to Power Systems (PMAPS) IEEE; 2016. p. 1–6.
[31] Rolfsman B. Combined heat-and-power plants and district heating in a deregulated electricity market. Appl Energy 2004 May;78(1):37–52.
[32] Hellmers A, Zugno M, Skajaa A, Morales JM. Operational strategies for a portfolio of wind farms and CHP plants in a two-price balancing market. IEEE Trans Power Syst. 2016;31(3):2182–91.
[33] Kumbartzky N, Schacht M, Schulz K, Werners B. Optimal operation of a CHP plant participating in the German electricity balancing and day-ahead spot market. Eur J Oper Res. 2017 Aug;261(1):390–404.
[34] Zugno M, Morales JM, Madsen H. Commitment and dispatch of heat and power units via affinely adjustable robust optimization. Comput Oper Res. 2016;75:191–201.
[35] Sorknæs P, Lund H, Andersen AN. Future power market and sustainable energy solutions – The treatment of uncertainties in the daily operation of combined heat and power plants. Appl Energy 2015 Apr;144:129–38.
[36] Haakana J, Tikka V, Lassila J, Partanen J. Methodology to analyze combined heat and power plant operation considering electricity reserve market opportunities. Energy 2017 May;127:408–18.
[37] DONG Energy. The Avedøreværket CHP plant. Denmark. 2008.
[38] Danish Energy Agency. District heating assessment tool (DHAT). Available at: https://ens.dk/en/our-responsibilities/global-cooperation/district-heating-assessment-tool-dhat.