Integrated pricing mechanism for combined electric and heat systems considering heat time delays.

Pingping Xie*, Tian Mao, Peizheng Xuan, Jin Zou, and Siyu Lu

Electric Power Research Institute, China Southern Power Grid, Guangzhou, Guangdong, 510663, China

*Corresponding author’s e-mail: xiepp@csg.cn

Abstract. Combined electric and heat systems can significantly improve fuel efficiency and reduce carbon emission by making use of complementary properties of electricity and heat. However, many current papers on the energy market mechanism do not consider the heating price, while some do not address the challenges of heat time delays on prices, which may impede the benefits of system operators as well as users. Therefore, in this paper, we extend the electric local marginal price (LMP) to the integrated LMP (ILMP) for electricity and heat in combined electric and heat systems considering heat time delays and network constraints. The results of case studies demonstrate the proposed mechanism can provide fair electricity and heat prices which can reflect generation cost, power loss, network congestion, and time delays.

1. Introduction

1.1. Motivation

In recent years, with the large-scale deployment of combined heat and power (CHP) units, electric boilers, and heat pumps, the coupling between electric power systems and heating systems have become tighter and tighter. For example, in Jilin Province, China, more than 70% of heat load is supplied by the CHP unit [1]. With no doubt, such a tight coupling between electricity and heat benefits us by reducing both generation cost and carbon emission. At the same time, it leads to problems in the pricing mechanism: How to decide the price of heat?

Different countries have provided different solutions to this problem. For example, the United States, Japan, British, and Germany allow CHP units to bid as thermal generators and give them profit subsidies for heat prices. A few countries such as Finland, Sweden, and Denmark allow liberal heat markets to decide the price of heat. [2] Also, some countries try to establish an integrated electricity and heat market. The integrated electricity and heat market at Copenhagen allows the operator to jointly dispatch of electric power systems and heating systems and the users to decide the price of electricity and heat. [3] However, the heat prices in the above market mechanisms are not local marginal prices (LMPs) which can give a fair price reference for operators and users but the unilateral and nontransparent prices decided by the operators or the government, for example, government regulated prices, which may impede the benefits of generators as well as users. Therefore, it is essential to adopt the LMPs mechanism for the electricity and heat prices in combined electric and heat systems.
1.2. Literature review
On the research of integrated pricing mechanism, the problem is how to reflect the relation between the electricity price and the heat price. Some liberal electricity markets like PJM in the U.S. and NEM in Australia adopt the LMP pricing mechanism for electricity prices, but they do not have similar mechanisms for heat prices. The Demark has implemented a double settlement integrated pricing market mechanism for several years, but the LMP mechanism is not adopted, which cannot accurately reflect the congestions and loss of heating systems. [2] Another idea to deal with the integrated pricing mechanism is the benefit-to-heat (BTH) mechanism applied in Sweden and Finland, which calculates the heat price using the difference in overall costs and the electricity generation costs. However, the BTH mechanism has the assumption that the electricity generation is determined by heat generation, and the heat is the main product in the combined electricity and heat system. When these two assumptions are not satisfied, this method cannot accurately reflect the price of the heat. [3]

Some researchers have proposed integrated pricing mechanism by extending the LMP mechanism in electric power systems to the combined electric and heat systems. They first establish integrated optimization models for combined electric and heat systems and then calculate the ILMP of electricity and heat. For example, paper [3] has summarized several integrated pricing models based on the energy hub (EH), however, the EH model simplifies the electric and heat network, which is not accurate to calculate the LMP of electricity and heat. Authors of [4] propose the concept of the generalized local marginal price (GLMP) by extending electric LMP to combined electric and heat systems. However, it does not consider the time delays in the heating networks. Paper [3] has discussed how to find the equilibrium point for the separated electricity market and heat market and the use of two stage optimization to study the impact of demand response on LMP. However, it is not practical to consider electric and heat demand response simultaneously in the separated electricity and heat markets. To address the challenges in [6], paper [5] proposes a distributed scheduling framework to calculate the electricity price and the heat price in a combined electric and heat system. However, it still fails to consider the time delays in the heating system, either.

1.3. Contributions
This paper proposes an integrated pricing mechanism for combined electric and heat systems considering network constraints and time delays in the heating system.

First, we propose the ILMP mechanism for electricity and heat prices by extending the LMP in the electric power system, which can fairly calculate the electric and heat prices by incorporating generation component, loss component, congestion component, and loss component.

Second, since the heating system has a large inertia and long-time dynamic process, we consider the influence of time delay on the electricity and heat prices. Moreover, the heat network constraints and the widely-adopted varying mass flow adjustment is considered in the proposed mechanism, which means the mass flow can be time-varying.

2. Materials and methods

2.1. Clearing mechanism for the integrated thermoelectric energy market

2.1.1. Structure of integrated energy market. In the integrated energy market, independent system operators collect bids and product supply information from power production companies, heat production companies, cogeneration companies, energy retailers, and consumers, and clear them in the wholesale market. Local electric marginal price (LEMP) and local heating marginal price (LHMP) are transmitted to the two networks. Due to transaction costs, only large-scale users directly participate in the wholesale market, and other consumers are free to choose retailers to buy electricity and heat.

This article discusses the wholesale day-ahead market. Market participants include power production companies, thermal power production companies, cogeneration companies, independent operators (ISO), retailers (retailers), and large-scale power users. The day-ahead scheduling plan is formed. Both the heat
market and the electricity market are scheduled for one hour, with centralized scheduling and joint clearing.

2.1.2. Assumptions and simplification of market structure. Assumptions and simplification are shown below.

1) The optimal power flow problem is a steady-state problem, and the unit commitment problem is beyond this article. In a district thermal system, the direction of mass flow has been preset. The direction of mass flow and the unit commitment problem are both integer programming problems. This article will not explore this.

2) Inelastic demand: The pricing method of LMP mainly focuses on the operator decomposition problem after the optimal power flow of economic dispatch under the determined demand.

3) Don't consider the access to renewable energy for now: this model is a deterministic pricing strategy.

4) A day-ahead integrated energy market is discussed in the article, and the dispatch scale is one hour. The electricity market and the heat market are cleared at the same time.

2.1.3. Market clearing mechanism. The integrated energy market discussed in this article is a market that includes regional thermal systems and power systems.

The coupling factor that links the two systems is the combined heat and power unit (CHP). The market clearing mechanism is based on economic dispatch where constraints are considered and the objective function is minimized. At the same time, market participants should have an incentive to follow the instructions of the economic dispatch. Consumers will pay the centralized independent operators according to the calculated corresponding GLEMP and GLHMP for using energy. The combined heat and power units receive income from centralized independent operators based on the GLEMP and GLHMP, and at the same time obey the schedule before the day.

2.2. Models of economic dispatch

2.2.1. Physical model. A physical model considering the characteristics of the electricity and heating network is introduced.

(1) Electricity network

The power flowing from i to j using the form of node phase angle and its thermal constraint are shown as (1).

\[ P_{ij,t} = B_{ij} (\theta_{ij,t} - \theta_{ji,t}) \quad \forall ij \in \tau_{line}, \forall j \in \tau_{bus}, 1 \leq t \leq T \quad P_{ij,t}^2 \leq \bar{P}_{ij}^2 \]  

(1)

The node power balance at node i is shown as (2).

\[ P_{G,i,t} - P_{D,i,t} = \sum_{j \in \tau} P_{ij,t} = A P \quad \forall i \in \tau_{bus}, \forall ij \in \tau_{line}, t \in T \]  

(2)

(2) Heating network

Inlet temperatures of pipelines and temperatures of nodes follow formula (3) and (4).

In (3) and (4), the \( \tau_{S,j,i} \) and \( \tau_{R,j,i} \) represent the inlet temperature of pipeline j in supply/return network.

\[ T_{i,t}^S = T_{i,t}^S \quad j \in P_S \cap L_S (i), i \in H, t = t \leq T \]  

(3)

\[ T_{i,t}^R = T_{i,t}^R \quad j \in P_R \cap L_R (i), i \in H, t = t \leq T \]  

(4)

Load nodes are subjected to formula (5) and (6).
\[ m_{j,t} \] represents the mass flow rate in pipeline \( j \). \( \pi_{i,t} \) represents the mass flow rate of node \( i \).

\[
\sum_j m_{j,t} \tau_i^{S_j} = \sum_j m_{j,t} \tau_i^{SE_j} \quad \forall i \in H, j \in P_S \cap I_S(i), 1 \leq t \leq T
\]  

(5)

\[
(\pi_{i,t} + \sum_j m_{j,t} \tau_i^{R_j}) = (\pi_{i,t} \tau_i^{NR}) + (\sum_j m_{j,t} \tau_i^{RE_j}) \quad \forall i \in H, j \in P_R \cap I_R(i), 1 \leq t \leq T
\]  

(6)

Source nodes are subjected to formula (7) and (8)

\[
\sum_j m_{j,t} \tau_i^{R_j} = \sum_j m_{j,t} \tau_i^{SE_j} \quad \forall i \in H, j \in P_R \cap I_R(i), 1 \leq t \leq T
\]  

(7)

\[
\sum_j m_{j,t} \tau_i^{R_j} = \sum_j m_{j,t} \tau_i^{SE_j} \quad \forall i \in H, j \in P_R \cap I_R(i), 1 \leq t \leq T
\]  

(8)

Consider the time-delay temperature mixing periods and heat loss, the outlet temperatures of pipelines in supply network and return network are shown as formula (9), refer to [8] for details.

\[
x_i = \left[ \exp \left( \frac{-\lambda_i \Delta t}{A_i \rho C_i} \right) \right]^{1/(\rho \gamma_i / C_i)}
\]  

(9)

Source nodes generate heat and load nodes consume heat according to formula (10).

\[
h_{i,t} = c_p \pi_{i,t} (T_{i,t}^{NS} - T_{i,t}^{NR}) \quad \forall i \in H, 1 \leq t \leq T
\]  

(10)

All nodes follow formula (11), \( m_{i \rightarrow k,t} \) represents the mass flow rate of pipeline (from \( i \) to \( k \)).

\[
H_{Gi,t} - H_{Di,t} = C_p \left[ \sum_{k \in I_{i,t}^{end}} m_{i \rightarrow k,t} \tau_i^{h} - \sum_{j \in I_{i,t}^{end}} m_{j \rightarrow i,t} \tau_j^{h} \right] \quad \forall i \in I_{end}, t \in T
\]  

(11)

2.2.2. Optimization model. An economic dispatch model based on the physical model is introduced.

1) Objective function

The objective function of the economic dispatch is to minimize the overall cost of generating heat and electricity as formula (12) shows.

\[
\min_{p_{i,t}, h_{i,t}} f = \sum_{i \in I, t \in T} C_{i,t} (p_{i,t}, h_{i,t})
\]  

(12)

The cost function is presented as a quadratic function, as formula (13) shows.

\[
C_{i,t} = \eta_{i,0} + \eta_{i,1} p_{i,t} + \eta_{i,2} p_{i,t}^2 + \eta_{i,3} h_{i,t} + \eta_{i,4} h_{i,t}^2 + \eta_{i,5} p_{i,t} h_{i,t}
\]  

(13)

2) Constraints

All operating points in the feasible region can be represented by a linear combination of vertices as formula (14) shows.

\[
B_{i,t} p_{i,t} + K_{i,t} h_{i,t} \leq v_{k,t} \quad \forall i \in G, 1 \leq t \leq T
\]  

(14)

Generators have specific capacities to decrease or increase their output.
Network structure and current constraints and thermal constraints are shown in formula (1). Node heat balance constraint is shown in formula (11). Temperature transfer constraint representing thermal time-delay and heat loss is shown in formula (9).

The node temperature constraint is shown in formula (16).

Optimization model
The optimization problem described in A) and B) can summarize as (3-21) shows.

\[
\begin{align*}
\text{CP:} & \quad \min_{P_G, H_G, X_p, X_H} F \\
\text{s.t.:} & \quad \varphi_p(P_G, X_p) = 0 \quad (17b) \quad \varphi_H(H_G, X_H) = 0 \quad (17c) \\
& \quad g(P_G, H_G) \leq 0 \quad (17d) \quad g_p(X_p) \leq 0 \quad (17e) \\
& \quad g_H(X_H) \leq 0 \quad (17f)
\end{align*}
\]

Function (17a) is the same as function (12). Constraint (21b) shows the balance of node power, representing formula (2). Constraint (17c) represents the balance of node heating, and is another form of formula (11). Constraint (17d) represents the generating constraints of CHP, which is another form of formula (14). Constraint (17e) is another form of formula (1), representing the structure of gird. Constraint (17f) represents the structure of the heating network, in another form of (16).

CP is a typical convex optimization problem, because the objective function, constraints are all convex functions, and the variables are all continuous variables.

2.2.3. Pricing model. A pricing model derived from the optimization model is introduced.

1) Simple Problem
We mainly focus on the influence CHP has on the output of power and heat as well as the energy market, so we simplify the CP (Complete Problem) optimization model and get a SP (simple problem) without considering the network constraints to make the coupling influence of CHP more clear.

\[
\begin{align*}
\text{SP:} & \quad F = \min_{P_G, H_G} f1(P_G) + f2(H_G) + f3(P_G, H_G) \\
\text{s.t.:} & \quad \lambda_p : 1^T P_G = 1^T P_D \quad (19) \quad \lambda_h : 1^T H_G = 1^T H_D \quad (20) \quad \mu : g(P_G, H_G) \leq 0 \quad (21)
\end{align*}
\]

The objective function (18) is to minimize the generating cost, f1/f2/f3 means the cost of electricity/heat/coupling generating.

Constraint (19) refers to node heat balance constraint (17b) without considering heat network loss constraints, and (20) refers to node power balance constraint (17c) without considering electricity constraints.
network loss constraints. Since network constraints are not considered, the congestion and loss fees are
not taken into account. Constraint (21) refers to (17d) which represents the feasible domain constraints
for productivity devices.

According to KKT, the optimization solution satisfies (22) (23), and \( \mu \geq 0 \).

\[
LMEP = \lambda_p = \frac{\partial f^1}{\partial P_G} + \frac{\partial f^3}{\partial P_G} + \mu \frac{\partial g^*}{\partial P_G} \quad (22) \quad LMHP = \lambda_h = \frac{\partial f^2}{\partial H_G} + \frac{\partial f^3}{\partial H_G} + \mu \frac{\partial g^*}{\partial H_G} \quad (23)
\]

We discuss the price in two conditions:\(1) \mu > 0 \quad (2) \mu = 0 \).

(1) \( \mu = 0, \ g^* < 0 \)

Constraint (21) is not active, CHP operates inside the domain, CHP can adjust its heat and
electricity output, and the LMP satisfies (24) and (25).

\[
LMEP = \lambda_p = \frac{\partial f^1}{\partial P_G} + \frac{\partial f^3}{\partial P_G} \quad (24) \quad LMHP = \lambda_h = \frac{\partial f^2}{\partial H_G} + \frac{\partial f^3}{\partial H_G} \quad (25)
\]

(2) \( \mu > 0, \ g^* = 0 \)

Constraint (21) is active, CHP operates on the boundaries of the domain.

\[
\cos t_p = \frac{\partial f^1}{\partial P_G} + \frac{\partial f^3}{\partial P_G} \quad (26) \quad \cos t_h = \frac{\partial f^2}{\partial H_G} + \frac{\partial f^3}{\partial H_G} \quad (27)
\]

\[
LMEP = \lambda_p = \cos t_p + \mu \frac{\partial g^*}{\partial P_G} \quad (28) \quad LMHP = \lambda_h = \cos t_h + \mu \frac{\partial g^*}{\partial H_G} \quad (29)
\]

Operating conditions can be classified according to \( \mu \).

Single marginal unit represents that CHP is the marginal unit only in heat market or
electricity market to satisfy the marginal heat/electricity demand, and double marginal unit
represents that CHP is the marginal unit in both the heat and electricity market, and it has the
capacity to satisfy both the marginal demand in heat/electricity market.

2) Complete Problem

Adding network constraints into SP, complete problem (CP) is formed as (17) shows.

The Lagrangian operator corresponding to each constraint are shown as below.

\[
\lambda_p : (17b) \quad \lambda_h : (17c) \quad \mu : (17d) \quad \mu_p : (17e) \quad \mu_h : (17f)
\]

(1) Decomposition of LMP

Local marginal electricity price (LMEP) is always decomposed into three parts: the price of
generating electricity, the price of transmission loss, and the price of congestion, as shown in
(30).

\[
\lambda = \lambda_{\text{energy}} + \lambda_{\text{loss}} + \lambda_{\text{congestion}} \quad (30)
\]

The Decomposition technique with a reference node is adopted to get the standard form of
price as (31) shows.

\[
\lambda_{H-r} = \left[ \frac{\partial \varphi_{H-r}^T}{\partial X_H} \right] \left[ - \frac{\partial \varphi_{H-r}^T}{\partial X_H} \lambda_{H-r} - \frac{\partial g_{H-r}^T}{\partial X_H} \mu_h \right] \quad (31)
\]

The node heat balance constraint is shown as (32).
\[ \varphi_H' (H_G, X_H) = 0 \]  \hspace{1cm} (32)

Then change (31) into (33).

\[ \lambda_{h-r} = \left[ \left( \frac{\partial \varphi_H'}{\partial X_H} \right)^T \right] \left[ \left( \frac{\partial \varphi_H'}{\partial X_H} \right) \lambda_{h-r} - \left( \frac{\partial \varphi_H'}{\partial X_H} \right) \lambda_{h-r} \right] - \left( \frac{\partial \varphi_H'}{\partial X_H} \right)^T \frac{\partial \varphi_H'}{\partial X_H} \mu_h \]

\[ = \lambda_{\text{energy}} + \lambda_{\text{loss}} + \lambda_{\text{congestion}} \]  \hspace{1cm} (33)

Decompose the electricity price in the same way, and the electricity price is shown as (34).

\[ \lambda_{p-r} = \left[ \Delta_{p-r} \right] \left[ \left( \frac{\partial \varphi_P'}{\partial X_P} \right)^T \lambda_{p-r} + \lambda_{p-r} \right] - \left( \frac{\partial \varphi_P'}{\partial X_P} \right)^T \frac{\partial \varphi_P'}{\partial X_P} \mu_{p-r} \]

\[ = \lambda_{\text{energy}} + \lambda_{\text{loss}} + \lambda_{\text{congestion}} \]  \hspace{1cm} (34)

3. Results & Discussion

To verify the feasibility of the pricing model, the composition of GLMP and the marginal states of CHP units, a network of 6-node heat network and 6-node electricity network is used for simulation.

3.1 Extraction CHP operating at single marginal state

The CHP is operating at the boundary of the feasible domain so it is the single marginal unit in the heat market, the electricity output of CHP changes passively with the heating output of CHP.

The heating prices at node 1 and node 6 are shown in figure 1.

![Figure 1. LHMP at node 1 and node 6](image)

The heating price at node 6 (load node) is always higher than that at node 1 (generating node), because the heat loss component is always positive, increasing heat load leads to more heat load on the network. The heating prices have the same shape as the heat load, because the CHP is a single marginal unit, the heat price is influenced only by the heat generating.

3.2 Extraction CHP operating at double marginal state

The CHP is operating inside the feasible domain so it is double marginal unit both in heat and electricity market, the heating output and the electricity output change freely.

The heating prices at node 1 and node 6 are shown in figure 2, and the heat and electricity output are shown in figure 3.
Compared to figure 1, the heating prices at both node 1 and node 6 have the similar shape as the electricity load, because the CHP unit is also the marginal unit in the electricity market, the electricity output has an influence on the pricing of heat, and the coupling component has a high proportion in the heat price.

4. Conclusions
(1) Generalized local marginal price (GLMP) is composed of local electricity marginal price (LEMP) and local heating marginal heat price (LHMP) in the thermoelectric integrated energy market. For a marginal unit in a thermal system, the local marginal heat price includes the marginal production component and the thermoelectric coupling component. The heat price of the non-marginal unit is to increase the congestion component and network loss component based on the heat price of the marginal unit.

(2) If CHP is a single marginal unit of the thermal market, the main influencing factor of the price is the marginal production component, because the electricity is fixed by heat at this time, the power production does not affect the thermal production capacity. If it is a double-marginal unit, the thermoelectric coupling component has great influence on its price, which makes the heat price curve similar to the shape of the generation curve.

Acknowledge
This paper is one of the phased achievements of the research on unified modeling and optimized scheduling technology of China Southern Power Grid Company Limited’s technology project: Multi-energy flow with different characteristics (project No. : ZBKJXM20180579).

References
[1] Z. Li, W. Wu, M. Shahidehpour, J. Wang and B. Zhang, Combined Heat and Power Dispatch Considering Pipeline Energy Storage of District Heating Network, [J]. IEEE Transactions on Sustainable Energy, 2016, 7(1):12.
[2] Wang J, You S, Zong Y, et al. Investigation of real-time flexibility of combined heat and power
plants in district heating applications[J]. Applied Energy, 2019, 237:196-209.

[3] Li R, Wei W, Mei S, et al. Participation of an Energy Hub in Electricity and Heat Distribution Markets: An MPEC Approach[J]. IEEE Transactions on Smart Grid, 2018, PP(99):1-1.

[4] Deng L, Sun H, Chen R, et al. Research on nodal energy price of combined heat and power system for Energy Internet[J]. Power Syst. Technol, 2016, 40: 3375-3382.

[5] Cao Y, Wei W, Wu L, et al. Decentralized Operation of Interdependent Power Distribution Network and District Heating Network: A Market-Driven Approach[J]. IEEE Transactions on Smart Grid, 2018.

[6] Yue C, Wei W, Feng L, et al. Energy Trading and Market Equilibrium in Integrated Heat-Power Distribution Systems[J]. IEEE Transactions on Smart Grid, 2018:1-1.

[7] Z. Li, W. Wu, J. Wang, B. Zhang and T. Zheng, "Transmission-Constrained Unit Commitment Considering Combined Electricity and District Heating Networks," in IEEE Transactions on Sustainable Energy, vol. 7, no. 2, pp. 480-492, April 2016, doi: 10.1109/TSTE.2015.2500571.