DESIGN OF AN AUCTION-BASED LOCAL ENERGY MARKET FOR INTEGRATED ELECTRICITY AND HEAT NETWORKS COORDINATED WITH WHOLESALE MARKET

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ABSTRACT

This article presents a market-based framework for coupling of electricity and heat sectors at the local level via power-to-heat (P2H) units. The considered local energy market (LEM) is designed based on an auction-based energy trading process which is settled by the integrated energy system operator (IESO) with the objective of social welfare maximization. Moreover, as part of the suggested mechanism, the coordination between the IESO and the transmission system operator (TSO) is considered to evaluate the mutual impact of the designed LEM on the wholesale electricity market (WEM) and vice versa. To this end, a bi-level programming model is employed, in which the LEM clearing problem is implemented at its upper level (UL) while the WEM clearing problem is executed at its lower level (LL). To assess the operation of the LEM and its coordination with the WEM, a case study is considered in which an integrated energy system (IES), including a 13-node electric distribution system and a 4-node district heating system, is connected to a 6-node transmission system.

Nomenclature

Sets

a	Set of nodes in district heating system
$e \in E$	Set of power participants in LEM
$g \in G$	Set of conventional producers in WEM
$h \in H$	Set of heat participants in LEM
i, j	Set of nodes in electric transmission system
$\hat{\imath}$	Set of nodes in electric transmission system connected to electric distribution system
$ld \in LD$	Set of loads in electric distribution system
$lh \in LH$	Set of loads in district heating system
$lt \in LT$	Set of loads in electric transmission system
n, m	Set of nodes in electric distribution system
$\hat{n}$	Set of nodes in electric distribution system connected to electric transmission system
$t \in T$	Time

Parameters

b_{ij}	Susceptance of lines in electric transmission system
b_{nm}, g_{nm}	Susceptance/conductance of lines in electric distribution system
C_W	Specific heat capacity of water
m	Mass flow rate in district heating system
P_{LD}, P_{LH}, P_{LT}	Demand of electric distribution/district heating/ electric transmission system
$q_E^{Bid\ max/Offer\ max}$	Max bid/offer of power participants in LEM
q_G^{max}	Max offer of conventional producers in WEM
$q_H^{Offer\ max}$	Max offer of heat participants in LEM
V_{nom}	Nominal voltage of electric distribution system
$\lambda_E^{Bid}, \lambda_E^{Offer}$	Bid/offer price of power participants in LEM
λ_G	Offer price of conventional producers in WEM
λ_H^{Offer}	Offer price of heat participants in LEM

Variables

$C_{WEM}^{Bid}, C_{WEM}^{Offer}$	Submitted bid/offer price of IESO in WEM
dV	Voltage deviation
q_E^{Bid}, q_E^{Offer}	Bid/offer of power participants in LEM
q_G	Offer of conventional producers in WEM
q_H^{Offer}	Offer of heat participants in LEM
$q_{WEM}^{Bid}, q_{WEM}^{Offer}$	Accepted bid/offer of IESO in WEM
$Q_{WEM}^{Bid}, Q_{WEM}^{Offer}$	Submitted bid/offer of IESO in WEM
T_R, T_S	Return/supply temperature of nodes in district heating system
$\lambda_{LEM-E}, \lambda_{LEM-H}$	Electricity/heat LEM-clearing price
λ_{WEM}	WEM clearing price
θ, δ	Voltage angle in distribution/transmission system

INTRODUCTION

In order to manage a large amount of distributed energy resources (DERs) in restructured power systems and benefit from their flexibility service provision potential, the concept of LEM has been gaining increased interest [1]. In general, LEMs are one of the most promising solutions for ensuring flexibility at the distribution level, dominated by stochastic renewable energy resources. The reason is that these markets provide a transactive platform for local electricity exchange among various kinds of prosumers, such as dispatchable and non-dispatchable units as well as energy storage systems. In the meanwhile, nowadays, the emergence of power-to-X-to-power (P2X2P) technologies and their widespread exploitation at the local level allows other energy carriers, including heat and gas, to be traded in the LEMs as well [2]. Hence, several attempts have been made in recent years to design LEMs with good functionality and scalability. Accordingly, authors in [3]–[5] have proposed the LEM structure that supports peer-to-peer electricity exchange among several prosumers equipped with DERs and energy storage units with the objective of social welfare maximization for all market participants. Authors in [6]–[8] have presented the LEM framework, in which various independent financial entities, including aggregators and microgrids, are able to compete with one another to trade electricity with the distribution system operator (DSO) in the market and simultaneously pursue their conflicting objectives. On the other hand, authors in [9]–[11] have designed the centralized LEM for the optimal operation of integrated energy systems that enable the trade of electricity and heat among the entire participants of these two sectors with the aim of social welfare maximization. Finally, authors in [12]–[14] have suggested decentralized frameworks for the LEM design that provide the possibility of power and heat energy trading among these two systems considering their independent operation.

By and large, the organization of a variety of multi-carrier DERs, P2X2P units, and energy storage systems in LEMs helps IESOs to procure a considerable percentage of their required demand at the local level and only compensate for the shortage from the upstream grid or the WEM. Furthermore, it is possible for these operators to supply their surplus to the WEM in the form of offer packages and make a profit. On the other hand, by decreasing bids as well as increasing offers from the distribution side, the demand in the WEM is reduced, resulting in low energy prices in the TSO-level market. As a result, since the interaction between emerging LEMs and the WEM has potential benefits and importance, multiple recent research works have attempted to propose optimal solutions for the better coordination of distribution and transmission systems [15]–[17].

Considering the significance of LEMs and their two-way impact on the WEM, this article proposes a centralized two-sided auction-based LEM that not only facilitates the coupling of electricity and heat sectors to get benefit from multi-carrier DERs and P2X2P units but also takes into account its coordination with the WEM. To this end, a bi-level programming method is employed, in which the LEM clearing process by the IESO is implemented at its UL, while the WEM clearing process by the TSO is executed at its LL. The primary goal of this study is to assess the mutual influence of the designed LEM on the WEM and vice versa.

METHODOLOGY

As mentioned previously, a LEM is designed in this paper so that it integrates the electric distribution system and the district heating system through P2H units, such as combined heat and power (CHP) plant and electric boiler (EB). In the designed framework, the coordination of the LEM with the WEM is evaluated as well. For this purpose, a bi-level programming approach is utilized to consider both markets' clearing processes. The outline of the suggested model is demonstrated in Figure 1.

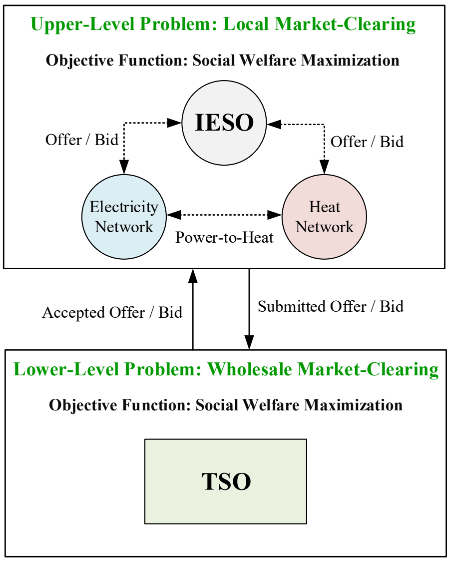

Figure 1. Outline of the proposed bi-level framework.

As shown in Figure 1, at the UL of the problem, the IESO is responsible for clearing the LEM with the objective of social welfare maximization and meeting the IES's power and heat demands in the presence of both the electric distribution system and the district heating system's technical constraints. The energy trading in the considered LEM is based on a two-sided auction-based format, in which the entire power and heat market participants are required to submit their offers and bids to the operator. In this procedure, the IESO's coordination with the TSO is also modeled so that this entity is able to submit its offers and bids to the WEM for energy exchange between distribution and transmission systems. In addition, at the LL of the problem, the TSO is responsible for clearing the WEM with the objective of social welfare maximization and meeting demands in the presence of the transmission system's technical constraints. The energy trading in the WEM is also based on a two-sided auction-based format, in which the entire market participants, including conventional power producers and IESO, are required to submit their offers and bids to the operator. In the following of this section, objective functions as well as operational and technical constraints of both levels are formulated mathematically.

A. UL Problem Formulation

The UL's objective function in Eq. (1) is the minimization of the minus social welfare.

$$\begin{aligned} Min \sum_{t\in T} \{ & \lambda_{WEM}(i=\hat{\imath},t) q_{WEM}^{Bid}(t) - \lambda_{WEM}(i=\hat{\imath},t) q_{WEM}^{Offer}(t) \\ & + \sum_{e\in E} [\lambda_E^{Offer}(e,t) q_E^{Offer}(e,t) - \lambda_E^{Bid}(e,t) q_E^{Bid}(e,t)] \\ & + \sum_{h\in H} [\lambda_H^{Offer}(h,t) q_H^{Offer}(h,t)]\}, \end{aligned} \tag{1}$$

This objective function is subject to a set of linear technical and operational constraints:

$$\begin{aligned} & q_{WEM}^{Bid}(t) - q_{WEM}^{Offer}(t) = \\ & \sum_{m:(n,m)\in\Delta_D} \{V_{nom}[dV(n,t) - dV(m,t)] g_{nm} \\ & \qquad -V_{nom}^2[\theta(n,t) - \theta(m,t)] b_{nm}\}, \\ & \lambda_{LEM-E}(n,t), \;\; \forall n = \hat{n}, t \end{aligned} \tag{2}$$

$$\begin{aligned} & \sum_{e:(e,n)\in E} [q_E^{Offer}(e,t) - q_E^{Bid}(e,t)] - \sum_{ld:(ld,n)\in LD} P_{LD}(ld,t) \\ & = \sum_{m:(n,m)\in\Delta_D} \{V_{nom}[dV(n,t) - dV(m,t)] g_{nm} \\ & \qquad -V_{nom}^2[\theta(n,t) - \theta(m,t)] b_{nm}\}, \\ & \lambda_{LEM-E}(n,t), \;\; \forall n \neq \hat{n}, t \end{aligned} \tag{3}$$

$$\begin{aligned} & \sum_{h:(h,a)\in H} q_H^{Offer}(h,t) = C_W m(a,t)\{T_S(a,t) - T_R(a,t)\}, \\ & \forall a \in Heat\ Station, t \end{aligned} \tag{4}$$

$$\begin{aligned} & \sum_{lh:(lh,a)\in LH} P_{LH}(lh,t) = C_W m(a,t)\{T_S(a,t) - T_R(a,t)\}, \\ & \lambda_{LEM-H}(a,t), \;\; \forall a \in Heat\ Exchanger\ Station, t \end{aligned} \tag{5}$$

$$Q_{WEM}^{Offer}(t) \geq 0, \;\; Q_{WEM}^{Bid}(t) \geq 0, \quad \forall t \tag{6}$$

$$C_{WEM}^{Offer}(t) \geq 0, \;\; C_{WEM}^{Bid}(t) \geq 0, \quad \forall t \tag{7}$$

$$0 \leq q_E^{Offer/Bid}(e,t) \leq q_E^{Offer\,max/Bid\,max}(e), \quad \forall e, t \tag{8}$$

$$0 \leq q_H^{Offer}(h,t) \leq q_H^{Offer\,max}(h), \quad \forall h, t \tag{9}$$

Eqs. (2)-(3) are the LEM power balance in the connected bus to the transmission system and the rest of the buses, respectively. Eqs. (4)-(5) are the LEM heat balance in heat stations and heat exchanger stations, respectively. Eqs. (6)-(7) are related to the IESO's submitted offer/bid packages to the WEM. Eqs. (8)-(9) restrict LEM power and heat participants' offers to their maximum quantity offers. Notably, technical constraints of electric distribution and district heating systems are adopted from [6],[10].

B. LL Problem Formulation

The LL's objective function in Eq. (10) is the minimization of the minus social welfare, as well.

$$Min \sum_{t \in T} \{ \sum_{g \in G} \lambda_G(g,t) q_G(g,t) \\ + C_{WEM}^{Offer}(t) q_{WEM}^{Offer}(t) - C_{WEM}^{Bid}(t) q_{WEM}^{Bid}(t) \}, \tag{10}$$

This objective function is also subject to a set of linear technical and operational constraints:

$$q_{WEM}^{Offer}(t) - q_{WEM}^{Bid}(t) = \sum_{j:(i,j) \in \Delta_T} \{ b_{ij} [\delta(i,t) - \delta(j,t)] \}, \\ \lambda_{WEM}(i,t), \ \ \forall i = \hat{\imath}, t \tag{11}$$

$$\sum_{g:(g,i) \in G} q_G(g,t) - \sum_{lt:(lt,n) \in LT} P_{LT}(lt,t) \\ = \sum_{j:(i,j) \in \Delta_T} \{ b_{ij} [\delta(i,t) - \delta(j,t)] \}, \\ \lambda_{WEM}(i,t), \ \ \forall i \neq \hat{\imath}, t \tag{12}$$

$$0 \leq q_{WEM}^{Offer}(t) \leq Q_{WEM}^{Offer}(t), \ \ 0 \leq q_{WEM}^{Bid}(t) \leq Q_{WEM}^{Bid}(t), \\ \forall t \tag{13}$$

$$0 \leq q_G(g,t) \leq q_G^{max}(g), \quad \forall g, t \tag{14}$$

Eqs. (11)-(12) are the WEM power balance in the connected bus to the distribution system and the rest of the buses, respectively. Eq. (13) limits the accepted offer/bid of the IESO in the WEM to its submitted offer/bid. Eq. (14) restricts conventional power producers' offers in the WEM to their maximum quantity offers. Notably, technical constraints of electric transmission system are adopted from [15].

The suggested bi-level model is re-formulated to a linear single-level model by Karush-Kuhn-Tucker conditions as well as the Strong Duality theory and the Big-M method, as stated in [6].

CASE STUDY

In this part, the provided model for the design of the LEM and its interaction with the WEM is applied to a system consisting of a 6-node electric transmission system, a 13-node electric distribution system, and a 4-node district heating system. Figure 2 illustrates the single-line diagram of the studied system.

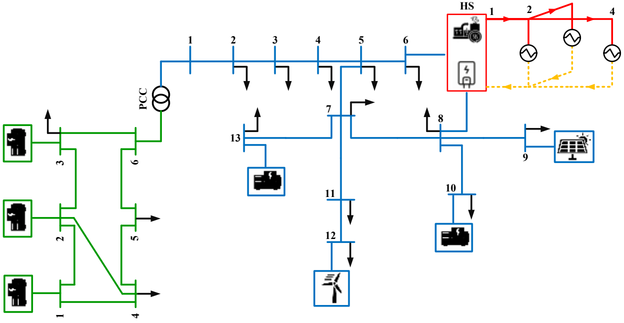

Figure 2. Topology of the IES connected to the transmission system.

As shown, the electric transmission system has three conventional producers (CPs) at nodes 1,2,3, the electric distribution system has two dispatchable generators (DGs), one wind turbine (WT), and one photovoltaic (PV) system at nodes 10,13,12,9, and finally, the district heating system has one CHP and one EB at the heat station, which is coupled to nodes 6 and 8 electric distribution system. The maximum offer/bid of these participants in their associated markets is shown in Table 1 and Figure 3. Moreover, the offer/bid prices of these units to the LEM and WEM are depicted in Figure 4. On the other hand, demand consumption of the IES, as well as the transmission system, are demonstrated in Figure 5.

Table 1. Maximum offer/bid of the LEM and WEM participants.

# Unit	Maximum Offer/Bid (MW)
DG 1	3.0
DG 2	2.0
CHP	2.0
EB	1.5
CP 1	14.0
CP 2	5.0
CP 3	12.0

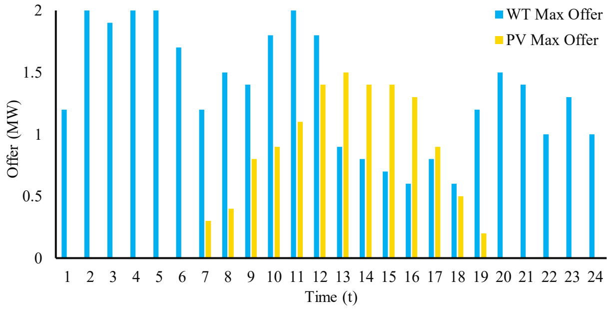

Figure 3. Maximum offer of the renewable resources in the LEM.

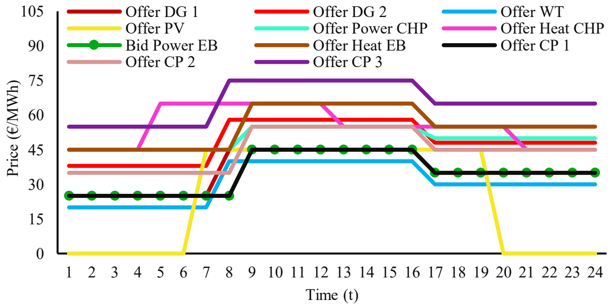

Figure 4. Offer/bid prices of market participants.

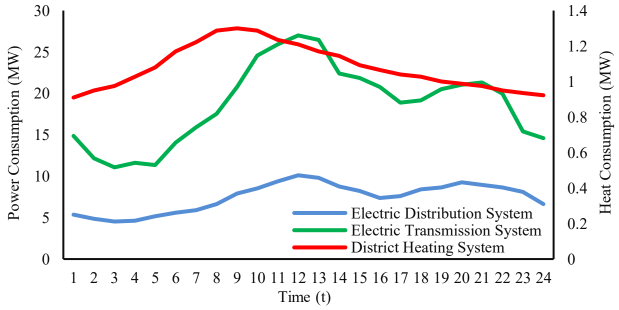

Figure 5. Load profiles of three systems.

In the end, it is assumed that the capacity of the line between the electric distribution system and the electric transmission system is confined to 3 MW.

In the following, the output results from the simulation are presented. In this paper, more attention is paid to the way of optimal interaction between these two markets, the optimal operation of the available resources in systems, as well as the impact of LEM and WEM prices on each other. In this regard, the accepted offer/bid of power participants in the LEM, as well as the accepted offer/bid of the IESO in the WEM, are represented in Figure 6. The area graph in this figure shows the electric distribution demand.

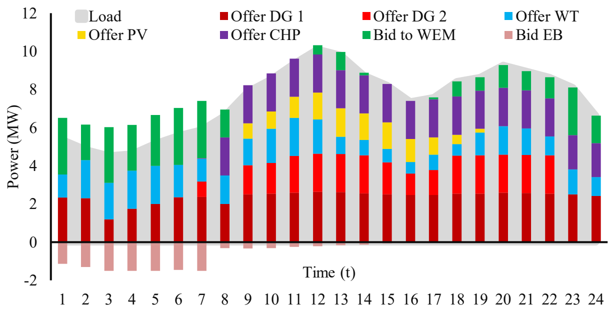

Figure 6. Operating power points in the LEM.

Based on Figure 6, on the studied day, the IESO acts as a power consumer in the WEM. Accordingly, in the early hours of the day, this entity has preferred to import more power from the WEM to consume in the EB and produce heat for the district heating system. This issue has occurred due to low WEM prices at these hours. In addition, since the offer prices of DG 1 and WT are lower than the rest of the LEM participants' offer prices, these two resources have been exploited whole the day, while DG 2 and CHP have been exploited more at peak hours. On the other hand, the accepted offer of heat participants in the LEM and district heating demand have been illustrated in Figure 7.

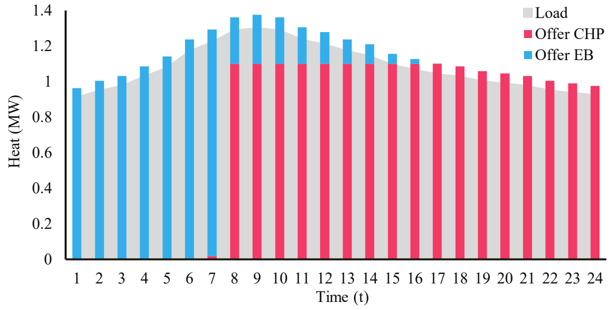

Figure 7. Operating heat points in the LEM.

Based on Figure 7, since the electricity price is low in the early hours of the day, the generated power in the LEM and imported power from the WEM has been transferred to heat by the existing EB to procure the peak heat demand of the system. By increasing the electricity price, the heat demand procurement has been assigned to the CHP. As clear in this figure, the generated heat at each hour has satisfied not only the demand but also heat loss in supply and return pipelines. Additionally, Figure 8 depicts the temporal and spatial variation of the electricity price in the LEM-clearing process.

Based on Figure 8, as expected, LEM-clearing prices have increased at peak hours. Additionally, as a result of congestion in lines of the electric distribution system, the LEM electricity price has changed in some nodes of the system. In order to better analyze the temporal level, prices in nodes 10 and 12 of the electric distribution system over the whole day have been shown in Figure 9. In order to better analyze the spatial level, node prices in the electric distribution system at hours 12 and 21 have been shown in Figure 10.

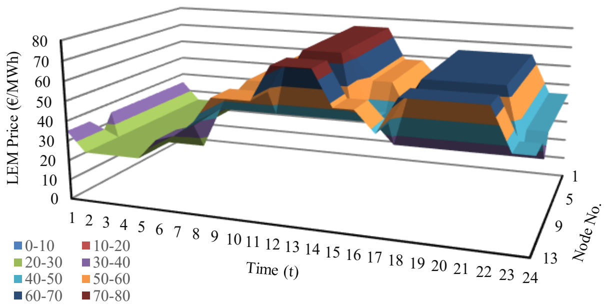

Figure 8. Electricity LEM-clearing price.

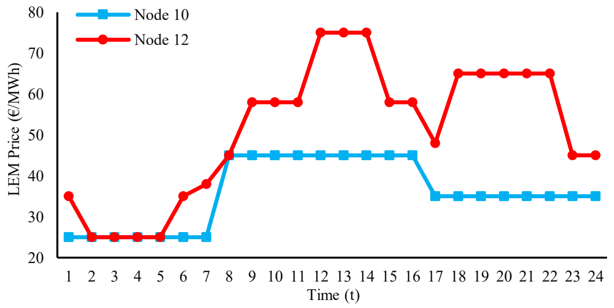

Figure 9. Temporal analysis of electricity LEM-clearing price.

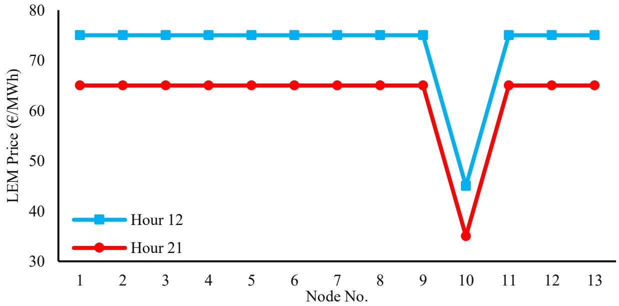

Figure 10. Spatial analysis of electricity LEM-clearing price.

Based on Figure 9, the electricity price in node 10 is equal to the offer price of DG 1, which is located at this bus. On the other hand, in hours that the line 8-10 distribution system is not faced with congestion, i.e., hours 3-4-5-8, the electricity prices in other nodes, including node 12, are also equal to the offer price of DG 1. However, in the rest of the hours that the line 8-10 distribution system is faced with congestion, the electricity prices in other nodes, including node 12, are equal to the offer prices of marginal producers in the LEM or WEM. For instance, at hour 1, the electricity price in node 12 is equal to the offer price of CP 2 in the WEM since other producers with lower prices are at their maximum production capacity. For another example, at hour 7, the electricity price in node 12 is equal to the offer price of DG 2 in the LEM. The important point here is that at this hour, CP 2 in the WEM, which has a lower offer price than DG 2 in the LEM, has not been able to determine the price of node 12. That is because the line between electric transmission and distribution systems is congested, and there is no possibility to import more power from the WEM to the LEM.

Based on Figures 10 and 6, at hours 12 and 21, all power participants in the LEM except for DG 1 are at their maximum production capacity. Hence, it is expected that

DG 1, as a marginal producer, determines the LEM price in different nodes. Nonetheless, due to congestion in the line 8-10, this unit has been able to merely affect node 10's price. Consequently, the IESO is forced to compensate for its shortage from the WEM, and the LEM-clearing prices are affected by WEM-clearing prices. So, at these two hours, CP 3, with offer prices of 65 €/MWh and 75 €/MWh, is the marginal producer in both transmission and distribution systems.

Finally, the accepted offer of participants in the WEM, as well as the temporal and spatial variation of the electricity price in the WEM-clearing process, are displayed in Figures 11 and 12, respectively.

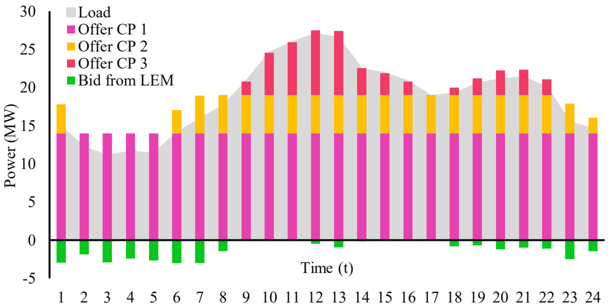

Figure 11. Operating power points in the WEM.

As shown in Figure 11, CP 1, which is the cheapest producer in the WEM, has been exploited with full capacity over the studied day. However, CP 3, which is the most expensive producer in the WEM, has been exploited only at peak hours.

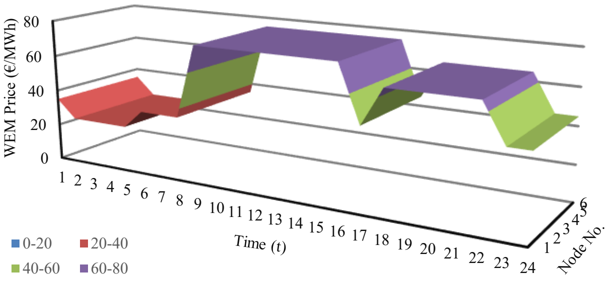

Figure 12. WEM-clearing price.

Based on Figure 12, WEM-clearing prices have increased at peak hours. Also, since none of the transmission system lines are congested, the WEM electricity prices are the same at different nodes.

CONCLUSION

The present paper suggested a LEM platform for the integration of electricity and heat sectors at the distribution level that considered this market's coordination with the WEM as well. For modeling the considered problem, a bi-level programming approach was utilized, in which the LEM and WEM-clearing processes are implemented at the UL and LL, respectively. This model was tested on an IES, including a 13-node electric distribution system and a 4-node district heating system, which is connected to a 6-node transmission system. The simulation results showed how WEM-clearing prices influence LEM-clearing prices.

Acknowledgment

The work of Sara Haghifam has been supported by the Fortum and Neste foundation.

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