Decentralized Demand Management Based on Alternating Direction Method of Multipliers Algorithm for Industrial Park with CHP Units and Thermal Storage

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***Abstract*—This paper proposes a decentralized demand management approach to reduce the energy bill of industrial park and improve its economic gains. A demand management model for industrial park considering the integrated demand response of combined heat and power (CHP) units and thermal storage is firstly proposed. Specifically, by increasing the electricity outputs of CHP units during peak-load periods, not only the peak demand charge but also the energy charge can be reduced. The thermal storage can efficiently utilize the waste heat provided by CHP units and further increase the flexibility of CHP units. The heat dissipation of thermal storage, thermal delay effect, and heat losses of heat pipelines are considered for ensuring reliable solutions to the industrial park. The proposed model is formulated as a multi-period alternating current (AC) optimal power flow problem via the second-order conic programming formulation. The alternating direction method of multipliers (ADMM) algorithm is used to compute the proposed demand management model in a distributed manner, which can protect private data of all participants while achieving solutions with high quality. Numerical case studies validate the effectiveness of the proposed demand management approach in reducing peak demand charge, and the performance of the ADMM-based decentralized computation algorithm in deriving the same optimal results of demand management as the centralized approach is also validated.**

***Index Terms*—Alternating direction method of multipliers (ADMM), combined heat and power (CHP) unit, demand management, industrial park, integrated demand response (IDR), thermal storage.**

Nomenclature

A. Indices and Sets

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$\Theta(j)$	Set of receiving nodes of distribution lines with the same sending node j
B	Set of distribution lines, i.e., $B=\{1,2,\ldots,\lvert B\rvert\}$
j,k,t	Indices of nodes, days, and time periods
$I,\lvert I\rvert$	Subset of buses connected to industrial users and total number of industrial users
(i,j)	Indices of sending and receiving nodes of distribution lines
K	Set of days, i.e., $K=\{1,2,\ldots,\lvert K\rvert\}$
n	Index of nodes
N	Set of nodes in power system, i. e., $N=\{1,2,\ldots,\lvert N\rvert\}$
N/I	Set of nodes in power system except nodes connected to industrial users
T	Set of time periods, i.e., $T=\{1,2,\ldots,\lvert T\rvert\}$

B. Continuous Variables

$\omega_{j,k,t}^{\mathrm{elec}},\omega_{j,k,t}^{\mathrm{heat}}$	Dual variables for electricity/heat in node j at time t of day k
C_j^{IU}	Total gas purchase cost of the j^{th} user from utilities over one month
$E_{k,t}^{\mathrm{TS}}$	Stored energy level of thermal storage at time t of day k
$F_{j,k,t}^{\mathrm{CHP}}$	Natural gas consumption of combined heat and power (CHP) units in node j at time t of day k
$H_{j,k,t}^{\mathrm{CHP}}$	Heat output of CHP units in node j at time t of day k
$H_{k,t}^{\mathrm{ch}},H_{k,t}^{\mathrm{dis}}$	Charging/discharging heat of thermal storage from/to all users at time t of day k
$H_{j,k,t}^{\mathrm{ch}},H_{j,k,t}^{\mathrm{dis}}$	Charging/discharging heat of thermal storage from/to user j at time t of day k
$H_{j,k,t}^{\mathrm{ch,ls}},H_{j,k,t}^{\mathrm{dis,ls}}$	Heat loss of pipelines connecting to user j when charging/discharging thermal storage at time t of day k
$l_{ij,k,t}$	Squared current magnitude of distribution line (i,j) at time t of day k
$P_{ij,k,t},Q_{ij,k,t}$	Active/reactive power flow on distribution line (i,j) at time t of day k

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$P_{j,k,t}^{\mathrm{CHP}}$ Power output of CHP units in node j at time t of day k

$P_{j,k,t}^{\mathrm{glob}}, H_{j,k,t}^{\mathrm{glob}}$ Auxiliary variables of node j at time t of day k

$P_{k,t}^{\mathrm{grid}}$ Industrial park electricity power purchased from utility at time t of day k

$\overline{P}^{\mathrm{m}}$ Monthly peak electricity demand

$P_{j,k,t}^{\mathrm{net}}, H_{j,k,t}^{\mathrm{net}}$ Net electricity/heat load of node j at time t of day k

$P_{j,k,t}^{\mathrm{PV}}, Q_{j,k,t}^{\mathrm{PV}}$ Active/reactive power output of photovoltaic (PV) panels in node j at time t of day k

$Q_{k,t}^{\mathrm{grid}}$ Reactive power delivered to industrial park by the utility at time t of day k

$Q_{j,k,t}^{\mathrm{SVG}}$ Reactive power output of static var generator (SVG) in node j at time t of day k

$u_{j,k,t}^{\mathrm{elec}}, u_{j,k,t}^{\mathrm{heat}}$ Scaled dual variables for electricity/heat in node j at time t of day k

$v_{j,k,t}$ Squared voltage magnitude of node j at time t of day k

C. Parameters

γ Attenuation coefficient of thermal storage

$\epsilon^{\mathrm{pri}}, \epsilon^{\mathrm{dual}}$ Tolerances of stopping criterion of alternating direction method of multipliers (ADMM) algorithm corresponding to primal residual and dual residual, respectively

$\eta^{\mathrm{ch}}, \eta^{\mathrm{dis}}$ Charging/discharging efficiency factors of thermal storage

η_j^{CHP} Electricity efficiency factor of CHP units in node j

η_j^{loss} Loss factor of CHP units in node j

λ^{gas} Natural gas price

$\lambda_t^{\mathrm{grid}}$ Electricity energy price of industrial park load (price of electricity purchased from utility grid)

λ^{m} Peak electricity demand charge of industrial park load

$\xi_{j,k,t}^{\mathrm{loss}}$ Heat loss coefficient of pipelines connecting to the user j

ρ^{LHV} Low heat value of natural gas

ρ_1, ρ_2 Penalty coefficients of ADMM algorithm

τ Iteration counter of ADMM algorithm

φ^{grid} Power factor of industrial park

Δt Length of each dispatching time slot of thermal storage

$\overline{E}^{\mathrm{TS}}, \underline{E}^{\mathrm{TS}}$ The maximum/minimum energy level of thermal storage

$H_{j,k,t}^{\mathrm{d}}$ Heat load of node j at time t of day k

$\overline{H}_{j,k,t}^{\mathrm{line}}$ The maximum heat power flow of pipelines connecting centralized thermal storage to node j at time t of day k

$\overline{H}^{TS}$ The maximum heat power output of thermal storage

$\bar{I}_{ij}$ The maximum current magnitude of distribution line (i,j)

$\overline{P}_j^{\mathrm{CHP}}, \underline{P}_j^{\mathrm{CHP}}$ The maximum/minimum electricity output of CHP units in node j

$P_{j,k,t}^{\mathrm{d}}, Q_{j,k,t}^{\mathrm{d}}$ Active/reactive power load of node j at time t of day k

$P_{j,k,t}^{\mathrm{PV,fcst}}$ Forecasted PV output in node j at time t of day k

$\overline{P}_j^{\mathrm{PV}}$ Active power capacity of PV in node j

$\overline{Q}_j^{\mathrm{SVG}}$ Reactive power capacity of SVG in node j

r_{ij}, x_{ij} Resistance/reactance of distribution line (i,j)

$\overline{S}_j^{\mathrm{PV}}$ Apparent power capacity of PV in node j

TD Thermal delay time of heat pipelines, which depends on pipeline parameters

$\overline{U}_j, \underline{U}_j$ The maximum/minimum voltage magnitude in node j

I. Introduction

INDUSTRIAL park (or industrial estate) is an area planned for industrial development, which is usually associated with significant energy demands, especially electricity and natural gas. In terms of electric energy consumption, industrial park in many countries such as China and the United States is usually charged by a two-part tariff (TPT) policy [1], [2]. In the TPT policy, the electricity bill consists of two components, i. e., the peak demand charge and the energy charge [3]. The first component is charged based on the maximum electricity demand in a billing cycle [4]. For example, if the maximum electricity demand in one month is 10 MW and the peak demand charge rate is 4.43 \$/kW (Xi'an, China), the total peak demand charge would be $\$4.43\times10^4$. The second component is charged based on the actual electric energy consumption in a billing cycle [5]. The charge rate could be different in different hours, also known as the time-of-use (TOU) tariff. In China, the TOU tariff usually contains three prices corresponding to peak, normal, and valley periods, respectively [6].

Indeed, for some large-scale industrial parks, the peak demand charge is usually higher than the energy charge, which can reach up to 50%-70% of the monthly electricity bill [1], [7]. Thus, effective demand management approaches for industrial park to lower the peak electricity demand have attracted a lot of attentions in recent years, which can not only help enhance economic gains, but also promote the sustainable development of industrial park.

Demand response (DR) has been traditionally recognized as the key technique to realize demand management of large industrial/commercial/residential customers [3], [8]. Indeed, the TOU policy mentioned above can be considered as one of the effective incentives to promote DR. TOU prices are issued by utilities to encourage consumers to use electricity more friendly with respect to different power system operation states. Utilities offer incentives (lower prices) to encourage users to move their flexible electricity consumptions from peak-load periods to valley-load periods [9]. Hence, it can shave the peak load and relieve the supply pressure during the peak-load periods [10]. Reference [11] proposes an optimization model to adjust the load level of households or small businesses and maximize their utility in response to the hourly electricity price. In [12], a TOU-based dynamic energy management approach is presented to implement residential DR, while a multi-TOU price structure is designed to deal with the rebound peaks of residential demand due to the synchronization of electricity production and consumption.

Another widely-used DR approach is to install battery storage assets in industrial park. Battery storage can store electric energy during low-price periods and release the stored electricity to supply users during high-price periods. Demand management approaches using battery storages have been studied in [6], [13], [14]. A linear programming-based demand management approach for commercial and industrial buildings is proposed in [6] using PV solar and battery storage solutions. Reference [13] studies the coupling of ground energy storages and fast charging units for electric vehicle (EV) to realize demand management and lessen the impact of EV loads on distribution networks. A dynamic programming-based battery storage operation framework is proposed in [14], aiming to minimize the TPT cost considering renewable generation and spot electricity price.

Moreover, due to the high efficiency of energy utilization, the integrated energy system (IES) has drawn increasing attentions by academia and energy industry in recent years [15]-[17]. IES brings together multiple energy carriers, e.g., electricity, natural gas, and thermal sources, via the coupling equipment such as combined heat and power (CHP) units. Different from the traditional viewpoint which treats different energy systems independently, IES examines how they can work collaboratively to optimize the entire energy infrastructure. To this end, the traditional DR idea is naturally extended to the integrated demand response (IDR) under the framework of IES [10], [18], [19]. Compared with DR, IDR does not solely rely on flexible electricity loads (ELs), as it can shave peak loads of different energy forms by controlling the coupling equipment of multi-energy carriers. For example, CHP units can respond to TOU prices and increase their electricity outputs to supply ELs during peak-load periods.

IDR techniques have also been studied in a few papers [10], [18], [20], [21]. Reference [10] introduces the basic concept of IDR and reviews the state-of-the-art research. Game models among smart energy hubs are proposed in [18], [20] to carry out IDR program in the integrated natural gas and electricity system. Reference [21] presents a modern energy management technique for electricity and natural gas networks based on the non-cooperative game theory. However, the researches mentioned above mainly focus on using IDR techniques to relieve the supply pressure of the utility during peak-load periods by shaving peak loads, while the benefit and advantage of IDR techniques for industrial park have been largely neglected. We note that as CHP units in industrial park usually work in the following heat load (FHL) mode, they present limited flexibility in adjusting electricity outputs which are directly restricted by the heat load (HL). Thus, CHP units have limited flexibility in providing IDR in response to TOU prices. Moreover, the traditional demand management approaches require all participants to directly submit their private data to the demand manager, which is also referred to as the centralized demand management approach. However, such centralized approach may only be suitable for smart homes and smart buildings, but not for the industrial parks studied in this paper. The reason is that most participants in industrial park usually come from different companies, who may not be willing to share their confidential demand data that could potentially lead to the leakage of private business information. Hence, it is of crucial importance to develop a decentralized demand management tool for protecting commercially confidential data of participants in industrial parks.

To address the challenges mentioned above, this paper proposes a decentralized demand management approach for industrial park with CHP units and thermal storage. Specifically, the IDR of CHP units and thermal storage is explored to manage the peak electricity demand, thus reducing electricity bill of the industrial park under the TPT policy. Our proposed model is built on an alternating current (AC) power flow of electrical distribution network via the second-order conic programming (SOCP) formulation. Moreover, the heat dissipation of thermal storage as well as thermal delay effect and heat losses of heat pipelines are also considered for ensuring reliable solutions to the industrial park. The main contributions of this paper are summarized as follows.

1) Aiming at the TPT policy for industrial park, we propose a new demand management model built on an SOCP-based AC power flow of electrical distribution network considering the IDR from CHP units. CHP units can increase their electricity outputs during peak-load periods when not operated in the FHL mode, which can reduce the peak demand charge and the total energy charge.

2) To utilize the excessive heat generated by CHP units more efficiently, a central thermal storage is adopted in industrial park to enable the effective heat sharing among all participants considering the heat dissipation of thermal storage, thermal delay effect, and heat losses of heat pipelines. More importantly, our proposed demand management model realizes the coordination between thermal storage and CHP units to grant more flexibility to CHP units.

3) The alternating direction method of multipliers (ADMM) algorithm is utilized to compute our proposed demand management model in a distributed manner while achieving solutions with high quality, which can protect the private data of all participants in demand management of industrial park.

4) Numerical case studies demonstrate that our proposed demand management approach can significantly reduce the peak demand charge and enhance economic gains for industrial park. Moreover, the effectiveness of our proposed ADMM-based decentralized computation algorithm is also validated, which can obtain the same optimal results as the centralized approach.

The rest of this paper is organized as follows. Section II introduces the centralized demand management of industrial park using CHP units and thermal storage. Section III discusses the ADMM-based decentralized demand management framework. Case studies are presented in Section IV. This paper is concluded in Section V.

II. Centralized Demand Management of Industrial Park

This section presents a centralized framework for industrial park demand management, which targets to efficiently manage the industrial park demand through the IDR of energy coupling equipment. Section II-A discusses the industrial park demand management with CHP units, and in Section II-B, the proposed approach is extended to involve the centralized thermal storage in industrial park.

A. Demand Management of Industrial Park with CHP Units

In this paper, we focus on an industrial park with $|I|$ individual users. Figure 1 shows the structure of such an industrial park. Each industrial user contains one CHP unit and photovoltaic (PV) panels to supply HL and EL. CHP units from individual users can control their outputs according to the TOU tariff. During peak-load (also peak-price) periods, CHP units can increase their electricity outputs to supply ELs, which will reduce the electricity purchase from the utility. This can reduce not only the peak demand charge but also the electricity energy charge. Hence, through the DR of CHP units, we can achieve the industrial park demand management and reduce the TPT cost.

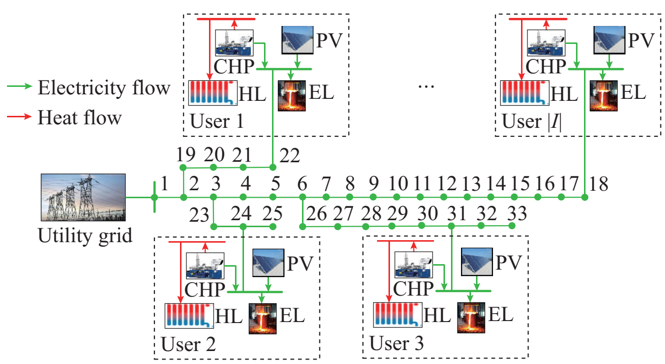

Fig. 1. Structure of industrial park with $|I|$ individual users.

The centralized demand management model for industrial park with CHP units is firstly proposed as shown in (1)-(15). The objective function (1) is to minimize the total cost of industrial park over one month, including the electricity consumption cost and the natural gas consumption cost. Under the TPT policy, the electricity consumption cost consists of two parts, i. e., the electricity energy charge denoted by the first term in (1), and the peak demand charge denoted by the second term in (1). The natural gas consumption cost includes the gas consumption charge of all CHP units, as shown in the third term of (1).

$$\min\left(\sum_{k,t}\lambda_t^{\text{grid}}P_{k,t}^{\text{grid}}+\lambda^{\text{m}}\overline{P}^{\text{m}}+\sum_{j\in I,k,t}\lambda^{\text{gas}}F_{j,k,t}^{\text{CHP}}\right) \tag{1}$$

s.t.

$$\begin{cases}P_{j,k,t}^{\text{CHP}}+P_{j,k,t}^{\text{PV}}+P_{j,k,t}^{\text{net}}=P_{j,k,t}^{\text{d}} & \forall j\in I,\forall k,\forall t\\ Q_{j,k,t}^{\text{SVG}}+Q_{j,k,t}^{\text{PV}}=Q_{j,k,t}^{\text{d}} & \forall j\in I,\forall k,\forall t\end{cases} \tag{2}$$

$$H_{j,k,t}^{\text{CHP}}\geq H_{j,k,t}^{\text{d}}\quad \forall j\in I,\forall k,\forall t \tag{3}$$

$$\begin{cases}\underline{P}_j^{\text{CHP}}\leq P_{j,k,t}^{\text{CHP}}\leq\overline{P}_j^{\text{CHP}} & \forall j\in I,\forall k,\forall t\\ P_{j,k,t}^{\text{CHP}}=F_{j,k,t}^{\text{CHP}}\rho^{\text{LHV}}\eta_j^{\text{CHP}} & \forall j\in I,\forall k,\forall t\\ H_{j,k,t}^{\text{CHP}}=P_{j,k,t}^{\text{CHP}}\left(1-\eta_j^{\text{CHP}}-\eta_j^{\text{loss}}\right)/\eta_j^{\text{CHP}} & \forall j\in I,\forall k,\forall t\end{cases} \tag{4}$$

$$\begin{cases}0\leq P_{j,k,t}^{\text{PV}}\leq P_{j,k,t}^{\text{PV,fcst}} & \forall j\in I,\forall k,\forall t\\ \left|Q_{j,k,t}^{\text{PV}}\right|\leq\sqrt{\left(\overline{S}_j^{\text{PV}}\right)^2-\left(\overline{P}_j^{\text{PV}}\right)^2} & \forall j\in I,\forall k,\forall t\end{cases} \tag{5}$$

$$\left|Q_{j,k,t}^{\text{SVG}}\right|\leq\overline{Q}_j^{\text{SVG}}\quad \forall j\in I,\forall k,\forall t \tag{6}$$

$$\begin{cases}\sum_{n\in\Theta(j)}P_{jn,k,t}-\left(P_{ij,k,t}-r_{ij}l_{ij,k,t}\right)=-P_{j,k,t}^{\text{net}} & \forall j\in I,\forall k,\forall t\\ \sum_{n\in\Theta(j)}P_{jn,k,t}-\left(P_{ij,k,t}-r_{ij}l_{ij,k,t}\right)=0 & \forall j\in N/I,\forall k,\forall t\end{cases} \tag{7}$$

$$\sum_{n\in\Theta(j)}Q_{jn,k,t}-\left(Q_{ij,k,t}-x_{ij}l_{ij,k,t}\right)=0\quad \forall j\in N,\forall k,\forall t \tag{8}$$

$$v_{i,k,t}-2\left(r_{ij}P_{ij,k,t}+x_{ij}Q_{ij,k,t}\right)+\left(r_{ij}^2+x_{ij}^2\right)l_{ij,k,t}=v_{j,k,t}\quad \forall(i,j)\in B,\forall k,\forall t \tag{9}$$

$$\left\|\begin{matrix}2P_{ij,k,t}\\ 2Q_{ij,k,t}\\ l_{ij,k,t}-v_{i,k,t}\end{matrix}\right\|_2\leq l_{ij,k,t}+v_{i,k,t}\quad \forall(i,j)\in B,\forall k,\forall t \tag{10}$$

$$\begin{cases}\sum_{n\in\Theta(1)}P_{1n,k,t}=P_{k,t}^{\text{grid}} & \forall k,\forall t\\ \sum_{n\in\Theta(1)}Q_{1n,k,t}=Q_{k,t}^{\text{grid}} & \forall k,\forall t\end{cases} \tag{11}$$

$$\left|Q_{k,t}^{\text{grid}}\right|\leq P_{k,t}^{\text{grid}}\tan\varphi^{\text{grid}}\quad \forall k,\forall t \tag{12}$$

$$\underline{U}_j^2\leq v_{j,k,t}\leq\overline{U}_j^2\quad \forall j\in N,\forall k,\forall t \tag{13}$$

$$0\leq l_{ij,k,t}\leq\overline{I}_{ij}^2\quad \forall(i,j)\in B,\forall k,\forall t \tag{14}$$

$$P_{k,t}^{\text{grid}}\leq\overline{P}^{\text{m}}\quad \forall k,\forall t \tag{15}$$

Constraint (2) indicates the active and reactive power balance of each industrial user. Constraint (3) imposes that the CHP heat output of each user must satisfy its heat demand in order to guarantee the reliable heat supply. Constraints (4), (5), and (6) represent the operation constraints of CHP units [22], PV panels [23] and static var generator (SVG) units, respectively. Specifically, the first sub-equation in (4) restricts the electricity output range of CHP units; the second sub-equation in (4) formulates the energy conversion of CHP units from natural gas to electricity; and the heat output of CHP units is formulated as in the third sub-equation in (4). The active and reactive power outputs of PV panels for each user are constrained in (5); and (6) restricts the reactive power output range of SVG for each user.

Moreover, the SOCP-based AC power flow model as shown in (7)-(14) is used to simulate electrical distribution network in the industrial park. Specifically, (7) and (8) describe the nodal active and reactive power balance for each node in the electrical distribution network, respectively. The voltage drop on each distribution line is formulated in (9). Equation (10) represents the second-order conic relaxation of the nonlinear AC power flow constraint [24]; (11) formulates the nodal active and reactive power balance at the point of common coupling (PCC), which is indexed as the first node; (12) describes the power factor limits required by the utility; (13) restricts the squared voltage magnitudes of each node; and (14) restricts the squared current magnitudes of each distribution line. The monthly peak electricity demand is computed in (15), which is used to calculate the peak demand charge, i.e., the second term in (1).

B. Demand Management of Industrial Park with CHP Units and Centralized Thermal Storage

Although the proposed model in Section II-A can effectively manage industrial park electrical load through DR of CHP units, a large amount of heat generated by CHP units in the peak-load period could be abandoned. This is because, in order to reduce electricity purchase from the utility during the peak-load period, CHP units increase their electricity outputs, which simultaneously induce high heat outputs. However, the increased heat outputs of CHP units may exceed the actual heat demand of individual users. To this end, the excessive heat generated by CHP units could be abandoned, leading to low energy efficiency in industrial park. To deal with this issue, a centralized thermal storage is adopted in industrial park to store and share heat among all individual users, as shown in Fig. 2.

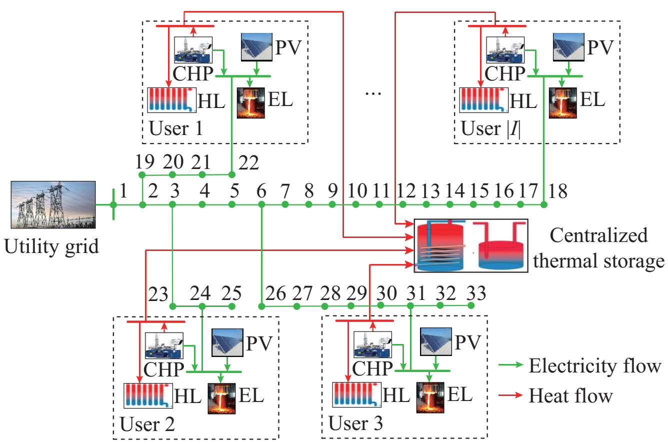

Fig. 2. Structure of industrial park with $|I|$ individual users and centralized thermal storage.

Thermal storage can store the surplus heat generated by CHP units during peak-load periods, which can be released during off-peak periods to supply individual users. The demand management model in Section II-A is enhanced as in (16)-(21) to involve the centralized thermal storage. The centralized thermal storage is connected to all users by heat pipelines. The heat dissipation of thermal storage and thermal delay effect, and the heat losses of heat pipelines are considered for ensuring reliable solutions to industrial park.

$$\begin{cases} \min\left(\sum_{k,t}\lambda_t^{\text{grid}}P_{k,t}^{\text{grid}}+\lambda^{\text{m}}\overline{P}^{\text{m}}+\sum_{j\in I,k,t}\lambda^{\text{gas}}F_{j,k,t}^{\text{CHP}}\right) \\ \text{s.t. } (2),(4)\text{-}(15),(17)\text{-}(21) \end{cases} \tag{16}$$

$$H_{j,k,t}^{\text{CHP}}+\left(H_{j,k,t-TD}^{\text{dis}}-H_{j,k,t-TD}^{\text{dis,ls}}\right)-\left(H_{j,k,t+TD}^{\text{ch}}+H_{j,k,t+TD}^{\text{ch,ls}}\right)=H_{j,k,t}^{\text{d}} \quad \forall j\in I,\forall k,\forall t \tag{17}$$

$$\begin{cases} H_{j,k,t}^{\text{dis,ls}}=\xi_{j,k,t}^{\text{ls}}H_{j,k,t}^{\text{dis}} & \forall j\in I,\forall k,\forall t \\ H_{j,k,t}^{\text{ch,ls}}=\xi_{j,k,t}^{\text{ls}}H_{j,k,t}^{\text{ch}} & \forall j\in I,\forall k,\forall t \end{cases} \tag{18}$$

$$\begin{cases} 0\le H_{j,k,t}^{\text{dis}}\le \overline{H}_{j,k,t}^{\text{line}} & \forall j\in I,\forall k,\forall t \\ 0\le H_{j,k,t}^{\text{ch}}+H_{j,k,t}^{\text{ch,ls}}\le \overline{H}_{j,k,t}^{\text{line}} & \forall j\in I,\forall k,\forall t \end{cases} \tag{19}$$

$$H_{k,t}^{\text{dis}}-H_{k,t}^{\text{ch}}=\sum_{j\in I}\left(H_{j,k,t}^{\text{dis}}-H_{j,k,t}^{\text{ch}}\right) \quad \forall k,\forall t \tag{20}$$

$$\begin{cases} 0\le H_{k,t}^{\text{ch}}\le \overline{H}^{\text{TS}} & \forall k,\forall t \\ 0\le H_{k,t}^{\text{dis}}\le \overline{H}^{\text{TS}} & \forall k,\forall t \\ E_{k,t}^{\text{TS}}=\text{e}^{-\gamma\Delta t}E_{k,t-1}^{\text{TS}}+\left(H_{k,t}^{\text{ch}}\eta^{\text{ch}}-\dfrac{H_{k,t}^{\text{dis}}}{\eta^{\text{dis}}}\right)\Delta t & \forall k,\forall t \\ \underline{E}^{\text{TS}}\le E_{k,t}^{\text{TS}}\le \overline{E}^{\text{TS}} & \forall k,\forall t \\ E_{k,t=1}^{\text{TS}}=E_{k,t=|T|}^{\text{TS}} & \forall k,\forall t \end{cases} \tag{21}$$

Constraint (17) formulates the heat power balance of each user. It is well-known that compared with electricity, heat is transported through pipelines at a relatively low speed, which could result in delays in the thermal transmission process, varying from several minutes to several hours [25]. The thermal delay effect in heat pipelines is considered in (17), where TD is mainly determined by heat pipeline parameters. Constraint (18) defines the heat loss in pipelines [26]. Constraint (19) limits the heat power flow in pipelines. Constraint (20) represents the stored and shared heat among all individual users. Constraint (21) describes the operation constraints of centralized thermal storage [27]. Specifically, the first two sub-equations in (21) restrict the charging and discharging heat power limits, respectively; the third sub-equation in (21) expresses the heat energy transition in thermal storage considering the heat dissipation process [28]; the fourth sub-equation in (21) constrains the stored heat energy limits of thermal storage; and the fifth sub-equation in (21) guarantees that the stored heat energy of thermal storage returns to the initial level in daily cycle. Note that the third term in the objective function (16) can naturally guarantee that centralized thermal storage will not charge and discharge heat simultaneously. This is because that charging and discharging heat simultaneously would lead to more consumption of natural gas in CHP units, which conflicts with the objective of minimizing the total cost of industrial park in (16).

III. ADMM-based Decentralized Demand Management of Industrial Park

The centralized demand management model described in Section II requires that all individual users shall directly submit some of their commercially confidential data such as EL data $P^{\mathrm{d}}_{j,k,t}$ and HL data $H^{\mathrm{d}}_{j,k,t}$ to the central demand manager of industrial park. The centralized demand management model is generally suitable for industrial park where all participants belong to a same company, so that data privacy will not be an issue. However, in most cases, participants in demand management of industrial park usually come from different companies, leading to the difficulty in implementing the centralized demand management approach. To deal with the above challenge, ADMM algorithm is used to compute the centralized model in Section II in a distributed manner, which can protect the commercially confidential data of all participants in demand management.

A. Reformulating Centralized Demand Management Model

To implement the decentralized demand management using ADMM algorithm, the centralized demand management model in Section II-B is firstly reformulated as a standard sharing problem [29] as in (22)-(29).

$$\begin{cases} \min\left(\sum_{j\in I} C_j^{\mathrm{IU}} + \sum_{k,t}\lambda_t^{\mathrm{grid}} P_{k,t}^{\mathrm{grid}} + \lambda^{\mathrm{m}}\overline{P}^{\mathrm{m}}\right) \\ \text{s.t. } (2)\text{-}(6), (7)\text{-}(15), (17)\text{-}(19), (21), (23)\text{-}(29) \end{cases} \tag{22}$$

$$\sum_{n\in\Theta(j)} P_{jn,k,t} - \left(P_{ij,k,t} - r_{ij} l_{ij,k,t}\right) = -P_{j,k,t}^{\mathrm{glob}} \quad \forall j\in I, \forall k, \forall t \tag{23}$$

$$H_{k,t}^{\mathrm{dis}} - H_{k,t}^{\mathrm{ch}} = \sum_{j\in I} H_{j,k,t}^{\mathrm{glob}} \quad \forall k, \forall t \tag{24}$$

$$C_j^{\mathrm{IU}} = \sum_{k,t}\lambda^{\mathrm{gas}} F_{j,k,t}^{\mathrm{CHP}} \quad \forall j\in I \tag{25}$$

$$P_{j,k,t}^{\mathrm{net}} = P_{j,k,t}^{\mathrm{d}} - P_{j,k,t}^{\mathrm{CHP}} - P_{j,k,t}^{\mathrm{PV}} \quad \forall j\in I, \forall k, \forall t \tag{26}$$

$$H_{j,k,t}^{\mathrm{net}} = H_{j,k,t}^{\mathrm{dis}} - H_{j,k,t}^{\mathrm{ch}} \quad \forall j\in I, \forall k, \forall t \tag{27}$$

$$P_{j,k,t}^{\mathrm{net}} = P_{j,k,t}^{\mathrm{glob}} : \omega_{j,k,t}^{\mathrm{elec}} \quad \forall j\in I, \forall k, \forall t \tag{28}$$

$$H_{j,k,t}^{\mathrm{net}} = H_{j,k,t}^{\mathrm{glob}} : \omega_{j,k,t}^{\mathrm{heat}} \quad \forall j\in I, \forall k, \forall t \tag{29}$$

Constraint (25) represents the total gas purchase cost of the j^{th} user ($\forall j\in I$) from utilities over one month. To reformulate the centralized model as the standard sharing problem in [29], we define two auxiliary variables $P_{j,k,t}^{\mathrm{glob}}$, $H_{j,k,t}^{\mathrm{glob}}$ and two dual variables $\omega_{j,k,t}^{\mathrm{elec}}$, $\omega_{j,k,t}^{\mathrm{heat}}$ in (28) and (29), respectively.

Note that the reformulated model as shown in (22)-(29) is mathematically equivalent to the centralized demand management model in Section II-B. Specifically, constraint (24) is the equivalence of the heat power balance constraint (20) of the centralized thermal storage.

B. ADMM-based Decentralized Algorithm for Industrial Park Demand Management

We further develop an ADMM-based decentralized demand management approach to solve the reformulated model as shown in (22)-(29). First, the augmented Lagrangian function of the reformulated model as shown in (22)-(29) is defined as in (30).

$$\begin{aligned} L_\rho = {} & \sum_{j\in I} C_j^{\mathrm{IU}} + \sum_{k,t}\lambda_t^{\mathrm{grid}} P_{k,t}^{\mathrm{grid}} + \lambda^{\mathrm{m}}\overline{P}^{\mathrm{m}} + \\ & \sum_{j\in I,k,t}\left[\omega_{j,k,t}^{\mathrm{elec}}\left(P_{j,k,t}^{\mathrm{net}} - P_{j,k,t}^{\mathrm{glob}}\right) + \frac{\rho_1}{2}\left(P_{j,k,t}^{\mathrm{net}} - P_{j,k,t}^{\mathrm{glob}}\right)^2\right] + \\ & \sum_{j\in I,k,t}\left[\omega_{j,k,t}^{\mathrm{heat}}\left(H_{j,k,t}^{\mathrm{net}} - H_{j,k,t}^{\mathrm{glob}}\right) + \frac{\rho_2}{2}\left(H_{j,k,t}^{\mathrm{net}} - H_{j,k,t}^{\mathrm{glob}}\right)^2\right] \end{aligned} \tag{30}$$

For the sake of discussion, (30) is written as the scaled form (31) by combining the linear and quadratic terms, where $u_{j,k,t}^{\mathrm{elec}} = \omega_{j,k,t}^{\mathrm{elec}}/\rho_1$ and $u_{j,k,t}^{\mathrm{heat}} = \omega_{j,k,t}^{\mathrm{heat}}/\rho_2$ are scaled dual variables.

$$\begin{aligned} L_\rho = {} & \sum_{j\in I} C_j^{\mathrm{IU}} + \sum_{k,t}\lambda_t^{\mathrm{grid}} P_{k,t}^{\mathrm{grid}} + \lambda^{\mathrm{m}}\overline{P}^{\mathrm{m}} + \\ & \frac{\rho_1}{2}\sum_{j\in I,k,t}\left(P_{j,k,t}^{\mathrm{net}} - P_{j,k,t}^{\mathrm{glob}} + u_{j,k,t}^{\mathrm{elec}}\right)^2 - \frac{\rho_1}{2}\sum_{j\in I,k,t}\left(u_{j,k,t}^{\mathrm{elec}}\right)^2 + \\ & \frac{\rho_2}{2}\sum_{j\in I,k,t}\left(H_{j,k,t}^{\mathrm{net}} - H_{j,k,t}^{\mathrm{glob}} + u_{j,k,t}^{\mathrm{heat}}\right)^2 - \frac{\rho_2}{2}\sum_{j\in I,k,t}\left(u_{j,k,t}^{\mathrm{heat}}\right)^2 \end{aligned} \tag{31}$$

Then, using the ADMM algorithm, (31) can be solved by iterating the following three updates:

1) Net-update

$$\begin{cases} \left\{P_{j,k,t}^{\mathrm{net}(\tau+1)}, H_{j,k,t}^{\mathrm{net}(\tau+1)}\right\} := \underset{P_{j,k,t}^{\mathrm{net}},\, H_{j,k,t}^{\mathrm{net}}}{\operatorname{argmin}}\, C_j^{\mathrm{IU}} + \\ \quad \frac{\rho_1}{2}\sum_{k,t}\left(P_{j,k,t}^{\mathrm{net}} - P_{j,k,t}^{\mathrm{glob}(\tau)} + u_{j,k,t}^{\mathrm{elec}(\tau)}\right)^2 + \\ \quad \frac{\rho_2}{2}\sum_{k,t}\left(H_{j,k,t}^{\mathrm{net}} - H_{j,k,t}^{\mathrm{glob}(\tau)} + u_{j,k,t}^{\mathrm{heat}(\tau)}\right)^2 \\ \text{s.t. } (2), (4)\text{-}(6), (17)\text{-}(19), (25)\text{-}(27) \end{cases} \tag{32}$$

2) Global-update

$$\begin{cases} \left\{P_{j,k,t}^{\mathrm{glob}(\tau+1)}, H_{j,k,t}^{\mathrm{glob}(\tau+1)}\right\} := \underset{P_{j,k,t}^{\mathrm{glob}},\, H_{j,k,t}^{\mathrm{glob}}}{\operatorname{argmin}} \sum_{k,t}\lambda_t^{\mathrm{grid}} P_{k,t}^{\mathrm{grid}} + \lambda^{\mathrm{m}}\overline{P}^{\mathrm{m}} + \\ \quad \frac{\rho_1}{2}\sum_{j\in I,k,t}\left(P_{j,k,t}^{\mathrm{glob}} - u_{j,k,t}^{\mathrm{elec}(\tau)} - P_{j,k,t}^{\mathrm{net}(\tau+1)}\right)^2 + \\ \quad \frac{\rho_2}{2}\sum_{j\in I,k,t}\left(H_{j,k,t}^{\mathrm{glob}} - u_{j,k,t}^{\mathrm{heat}(\tau)} - H_{j,k,t}^{\mathrm{net}(\tau+1)}\right)^2 \\ \text{s.t. } (7)\text{-}(15), (21), (23), (24) \end{cases} \tag{33}$$

3) u-update

$$\begin{cases} u_{j,k,t}^{\mathrm{elec}(\tau+1)} := u_{j,k,t}^{\mathrm{elec}(\tau)} + P_{j,k,t}^{\mathrm{net}(\tau+1)} - P_{j,k,t}^{\mathrm{glob}(\tau+1)} \\ u_{j,k,t}^{\mathrm{heat}(\tau+1)} := u_{j,k,t}^{\mathrm{heat}(\tau)} + H_{j,k,t}^{\mathrm{net}(\tau+1)} - H_{j,k,t}^{\mathrm{glob}(\tau+1)} \end{cases} \tag{34}$$

Note that the net-update (32) on $P_{j,k,t}^{\mathrm{net}}/H_{j,k,t}^{\mathrm{net}}$ can be performed in parallel over all users.

Finally, (32)-(34) are iteratively calculated to solve the industrial park demand management problem in a distributed manner.

C. Implementation of ADMM Algorithm

Two stopping criteria as shown in (35) are utilized in this paper to determine whether the ADMM iteration shall stop. The two stopping criteria can evaluate the convergence performance of primal residual and dual residual, respectively.

$$\begin{cases}\max\left\{\left|P_{j,k,t}^{\mathrm{net}(\tau+1)}-P_{j,k,t}^{\mathrm{glob}(\tau+1)}\right|,\left|H_{j,k,t}^{\mathrm{net}(\tau+1)}-H_{j,k,t}^{\mathrm{glob}(\tau+1)}\right|\right\}\le\epsilon^{\mathrm{pri}}\\ \max\left\{\left|P_{j,k,t}^{\mathrm{glob}(\tau+1)}-P_{j,k,t}^{\mathrm{glob}(\tau)}\right|,\left|H_{j,k,t}^{\mathrm{glob}(\tau+1)}-H_{j,k,t}^{\mathrm{glob}(\tau)}\right|\right\}\le\epsilon^{\mathrm{dual}}\end{cases} \tag{35}$$

The pseudocode of ADMM algorithm is shown in Algorithm 1.

Figure 3 illustrates the data exchange of ADMM-based decentralized demand management between the industrial park operator and individual users by using an example of two participants. Here, the industrial park operator coordinates all users to implement the decentralized demand management.

Algorithm 1: ADMM-based decentralized demand management of indus trial park

Input: forecasted EL $P_{j,k,t}^{\mathrm{d}}$, forecasted HL $H_{j,k,t}^{\mathrm{d}}$, and forecasted PV output $P_{j,k,t}^{\mathrm{PV,fcst}}$ for all users; electricity energy price $\lambda_t^{\mathrm{grid}}$, peak electricity demand charge λ^{m}, and natural gas price λ^{gas}; penalty parameters ρ_1, ρ_2, and the tolerance parameters ϵ^{pri}, ϵ^{dual}

Output: peak electricity demand $\overline{P}^{\mathrm{m}}$ for the month, which is used to calculate the peak demand charge of the month

Initialization: set the iteration counter $\tau=0$, initialize $u_{j,k,t}^{\mathrm{elec}(\tau)}$, $u_{j,k,t}^{\mathrm{heat}(\tau)}$, $P_{j,k,t}^{\mathrm{glob}(\tau)}$, $H_{j,k,t}^{\mathrm{glob}(\tau)}$, $P_{j,k,t}^{\mathrm{net}(\tau)}$, $H_{j,k,t}^{\mathrm{net}(\tau)}$ as 0

Iterative steps:

while (35) is not satisfied **do**
  Solve the net-update problem (32) in parallel
  Solve the global-update problem (33)
  Carry out the u-update step (34)
  Evaluate the stopping criteria (35)
  $\tau=\tau+1$
end while

Figure 3 shows that there is no data exchange among individual users, which can effectively avoid the leakage of private information such as EL and HL data. Instead, each user carries out its own net-update and sends the net EL and HL results to the industrial park operator. After collecting all net load information from individual users, the industrial park operator would carry out the global-update and broadcast the updated result back to individual users. Note that the information broadcast from the operator to users is non-sensitive. Thus, the proposed ADMM-based decentralized demand management of industrial park can prevent the leakage of sensitive private data to other industrial users.

IV. Simulation Results

In this section, our proposed ADMM-based decentralized demand management approach for the industrial park with CHP units and centralized thermal storage is validated through an exemplary industrial park with three industrial users. The electricity network is based on the IEEE 33-bus distribution system. One typical day from each week is selected, and then four typical days are collectively used to represent the entire month. Each selected typical day is the day with the hourly maximum EL in that week. Moreover, the typical day with the monthly maximum load among the four days is hereinafter referred to as the peak-load typical day. Penalty parameters of ADMM algorithm, i.e., ρ_1 and ρ_2, are both set to be 0.10. The tolerances ϵ^{pri} and ϵ^{dual} are both set to be 10^{-4}. The detailed data used for numerical tests can be accessed in [30]. The proposed demand management model is coded in MATLAB with YALMIP and then solved by CPLEX 12.8.0 on a desk computer with i7-8700 processor and 16 GB RAM.

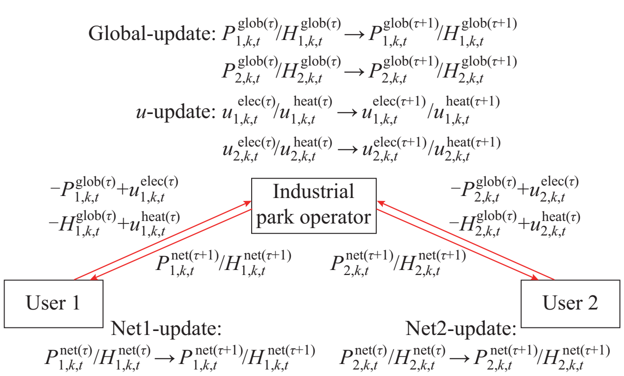

Fig. 3. Data exchange of ADMM-based decentralized demand management between industrial park operator and two illustrative industrial users.

A. Benefits of CHP Units for Demand Management of Industrial Park

The proposed demand management approach for industrial park intends to reduce the electricity cost under TPT by leveraging the DR ability of CHP units to TOU prices, as presented in Section II-A. To validate the effectiveness of our proposed demand management approach, the following two approaches are compared.

1) Directly purchasing electricity (DPE): in this approach, the industry park directly purchases electric energy from utilities. CHP units work in the FHL mode, and cannot provide IDR in response to TOU prices. That is, DPE does not realize demand management for industrial park.

2) Demand management by CHP units (DM_CHP): this is our proposed demand management approach with DR of CHP units, as discussed in Section II-A. During peak-load periods, CHP units could increase their electricity outputs to supply ELs.

Numerical results of the two approaches are illustrated in Table I and Fig. 4. Table I shows that the peak demand decreases by almost 6 MW, i. e., 21.58%, from DPE to DM_CHP. In addition, the total electric energy purchased from the utility and electricity energy charge is also reduced by 13.29% and 17.23%, respectively. This demonstrates the effectiveness of our proposed demand management approach. The main reason is that CHP units can increase their electricity outputs to supply ELs during peak-load periods when not operated in the FHL mode. Thus, as shown in Fig. 4(a) and Table I, both peak demand and electricity power purchased from the utility would significantly decrease, leading to the savings in the electricity cost (peak demand charge plus electricity energy charge). Although the natural gas cost, i. e., the fuel cost of CHP units, increases by 74.30%, the total cost of industrial park (electricity cost plus natural gas cost) still decreases by 5.12%, verifying that our proposed DM_CHP approach presents better performance than the traditional DPE approach.

The significant increase in the natural gas cost is mainly caused by the more natural gas consumption of CHP units to increase electricity output during peak-load periods. Indeed, CHP units also increase their heat outputs during peak-load periods, as indicated in Fig. 4(b), which exceeds the actual heat demand of all users. Thus, the excessive heat generated by CHP units has to be abandoned. As shown in Table I, the waste heat in DM_CHP is up to almost 1200 MWh, leading to significantly low energy efficiency in industrial park.

B. Benefits of Centralized Thermal Storage for Industrial Park Demand Management

To effectively utilize waste heat and increase the energy efficiency, we enhance our demand management approach by including a centralized thermal storage in industrial park, which can store and share heat among all users, as presented in Section II-B. To validate the effectiveness of the centralized thermal storage for industrial park demand management, the following two approaches are compared:

TABLE I
COMPARISON OF ENERGY BILL BETWEEN DPE AND DM_CHP

Item	Peak demand (MW)	Electricity purchased from utility (MWh)	Gas purchased from utility (10^6 m^3)	Electric energy provided by CHPs (MWh)	Heat energy provided by CHPs (MWh)	Waste heat (MWh)	Peak demand charge (10^5 \$)	Electricity energy charge (10^5 \$)	Electricity cost (10^5 \$)	Natural gas cost (10^5 \$)	Total cost (10^5 \$)
DPE	25.718	6057	0.354	1086	1545	0	1.139	5.853	6.991	1.129	8.120
DM_CHP	20.169	5252	0.618	1890	2697	1152	0.893	4.844	5.737	1.967	7.704
Increase/decrease of DM_CHP compared with DPE	21.58% decrease	13.29% decrease	74.30% increase	74.10% increase	74.59% increase		21.58% decrease	17.23% decrease	17.94% decrease	74.30% increase	5.12% decrease

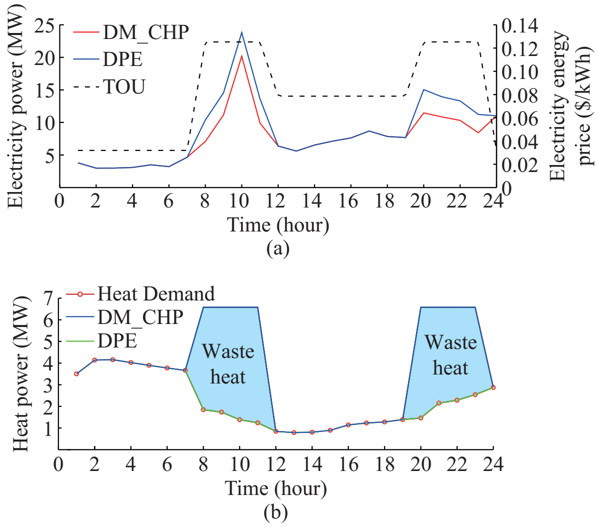

Fig. 4. Comparison of electricity power purchased from utility and heat power provided by CHPs between DPE and DM_CHP in typical peak-load day. (a) Electricity power purchased from utility. (b) Heat power provided by CHPs.

1) DM_CHP: this is the same approach studied in Section IV-A, i.e., the proposed demand management approach without centralized thermal storage.

2) DM_CHP and centralized thermal storage (DM_CHP&CTS): it represents our proposed demand management approach with DR of CHP units as well as centralized thermal storage, as shown in Section II-B.

Numerical results of the two approaches are illustrated in Fig. 5 and Table II. Table II shows that the peak demand result of DM_CHP&CTS (20.949 MW) is very close to that of DM_CHP (20.169 MW) with a difference of 0.8 MW (3.87%). Although the electricity cost (peak demand charge plus electricity energy charge) slightly increases by 6.90% from DM_CHP to DM_CHP&CTS, the natural gas cost of CHP units decreases significantly by almost 40%. Furthermore, no heat waste occurs in DM_CHP&CTS. Thus, the total cost of industrial park (electricity cost plus natural gas cost) further decreases by 4.07% after adopting the centralized thermal storage. The main reason is that the centralized thermal storage can efficiently utilize the waste heat, and augment the flexibility of CHP units. As shown in Fig. 5, centralized thermal storage can store excessive heat generated by CHP units during peak-load periods (from 8:00 to 11:00 and from 20:00 to 23:00), and release the stored heat energy to supply all users during off-peak-load periods. To this end, the waste heat is utilized more efficiently, leading to less natural gas consumption during off-peak-load periods.

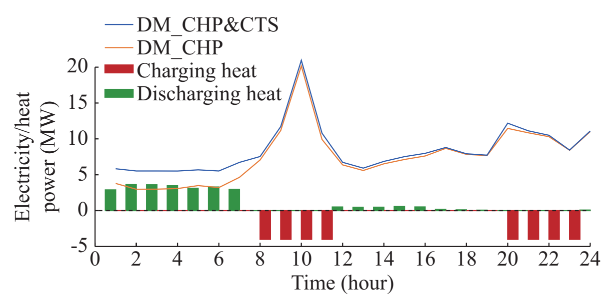

Fig. 5. Comparison of electricity power purchased from utility between DM_CHP and DM_CHP&CTS as well as charging/discharging heat power of centralized thermal storage in typical peak-load day.

C. Comparison Between Centralized and Decentralized Demand Management

In the centralized demand management approach, the participants in DR are from different companies, which makes it practically challenging to share private information. This motivates us to adopt the ADMM-based decentralized demand management approach in Section III, which can keep commercially sensitive information of participants from being disclosed. To validate the effectiveness of our proposed decentralized approach, the following two approaches are compared.

1) DM_CEN: it represents the centralized industrial park

TABLE II
COMPARISON OF ENERGY BILLS BETWEEN DM_CHP AND DM_CHP&CTS

Item	Peak demand (MW)	Electricity purchased from utility (MWh)	Gas purchased from utility (10^6 m^3)	Electric energy provided by CHPs (MWh)	Heat energy provided by CHPs (MWh)	Waste heat (MWh)	Peak demand charge (10^5 \$)	Electricity energy charge (10^5 \$)	Electricity cost (10^5 \$)	Natural gas cost (10^5 \$)	Total cost (10^5 \$)
DPE	20.169	5252	0.618	1890	2697	1152	0.893	4.844	5.737	1.967	7.704
DM_CHP	20.949	5926	0.395	1216	1727	0	0.927	5.206	6.133	1.258	7.391
Increase/decrease of DM_CHP&CTS compared with DM_CHP	3.87% increase	12.84% increase	36.03% decrease	35.65% decrease	35.96% decrease		3.87% increase	7.46% increase	6.90% increase	36.03% decrease	4.07% increase

demand management approach, as shown in Section II-B.

2) DM_ADMM: it represents the ADMM-based decentralized demand management approach, as shown in Section III.

Numerical results of the two approaches are illustrated in Fig. 6 and Table III. Figure 6 shows the evolution of peak demand over the iterative procedure of ADMM. From Fig. 6, it can be observed that DM_ADMM can obtain the same optimal peak demand as DM_CEN after 83 iterations within 150 s. This verifies that our proposed decentralized demand management approach presents a computationally efficient convergence performance, while identifying high-quality solutions.

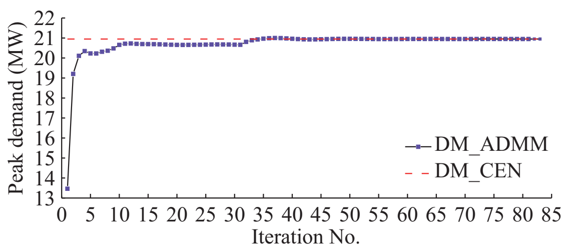

Fig. 6. Evolution of peak demand over iterative procedure of ADMM for demand management of industrial park.

TABLE III
COMPARISONS BETWEEN CENTRALIZED AND DECENTRALIZED APPROACHES FOR DEMAND MANAGEMENT OF INDUSTRIAL PARK

Approach	Peak demand (MW)	Total cost (10^5 \$)	Computation time (s)	Exchanged data	Exchanged volume
DM_CEN	20.949	7.391	5.240	$P^{\text{d}}_{j,k,t}$, $Q^{\text{d}}_{j,k,t}$, $H^{\text{d}}_{j,k,t}$, $P^{\text{PV, fcst}}_{j,k,t}$, $\overline{P}^{\text{CHP}}_{j}$, $\underline{P}^{\text{CHP}}_{j}$, $\overline{P}^{\text{PV}}_{j}$, $\overline{S}^{\text{PV}}_{j}$, $\overline{Q}^{\text{SVG}}_{j}$, η^{CHP}_{j}, η^{loss}_{j}, $P^{\text{CHP}}_{j,k,t}$, $F^{\text{CHP}}_{j,k,t}$, $H^{\text{CHP}}_{j,k,t}$, $P^{\text{PV}}_{j,k,t}$, $Q^{\text{PV}}_{j,k,t}$, $Q^{\text{SVG}}_{j,k,t}$	$10\|I\|\|K\|\|T\|+7\|I\|$
DM_ADMM	20.949	7.391	144.494	$P^{\text{net}}_{j,k,t}$, $H^{\text{net}}_{j,k,t}$, $-P^{\text{glob}}_{j,k,t}+u^{\text{elec}}_{j,k,t}$, $-H^{\text{glob}}_{j,k,t}+u^{\text{heat}}_{j,k,t}$	$4\|I\|\|K\|\|T\|$

From Table III, it can be observed that the decentralized approach via ADMM can obtain the same demand management results, i.e., the peak demand and the total cost, as the centralized approach. The computation time of DM_ADMM is about 145 s, which is significantly longer than that of DM_CEN. Considering that DM_ADMM is not run in real time, the computation performance of DM_ADMM is still acceptable for running such a decentralized algorithm in the energy management system (EMS) of industrial park. On the other hand, compared with DM_CEN, DM_ADMM has another advantage of protecting private data of all participants. Besides, the data exchanged in DM_ADMM only include the net electricity/heat power $P^{\text{net}}_{i,k,t}$ and $H^{\text{net}}_{i,k,t}$ as well as the intermediate results $-P^{\text{glob}}_{j,k,t}+u^{\text{elec}}_{j,k,t}$ and $-H^{\text{glob}}_{j,k,t}+u^{\text{heat}}_{j,k,t}$. On the contrary, the data exchanged in DM_CEN consist of many private data such as EL/HL curves $P^{\text{d}}_{i,k,t}$ and $H^{\text{d}}_{i,k,t}$ as well as CHP parameters $\overline{P}^{\text{CHP}}_{i}$ and $\underline{P}^{\text{CHP}}_{i}$. This means that our proposed decentralized approach can effectively protect commercially confidential data of all participants. Meanwhile, our proposed decentralized approach requires smaller volume of data exchange than the centralized approach, as shown in Table III. In our case study, with $|I|=3$, $|K|=4$, and $|T|=24$, the volume of data exchange decreases from 185644 bits in DM_CEN to 73728 bits in DM_ADMM. This can reduce the communication burden and bandwidth requirement, which verifies the effectiveness of our proposed ADMM-based decentralized approach.

D. Sensitivity Analysis of Key Parameters for Decentralized Demand Management Model

To verify the scalability of the proposed ADMM-based decentralized demand management approach for practical industrial park, sensitivity analysis is designed to study the impacts of different numbers of selected typical days as well as industrial users. The results are shown in Fig. 7 and Fig. 8.

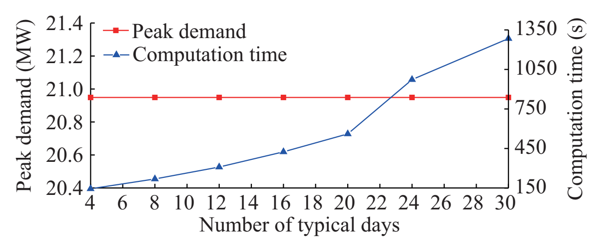

Fig. 7. Changes of peak demand and computation time with different numbers of typical days for ADMM-based decentralized approach.

Figure 7 shows that computation time of ADMM-based decentralized approach increases almost linearly with the number of selected typical days. The decentralized approach can obtain the optimal solution after 83 iterations within 1300 s, even if all days in a month are selected, i.e., 30 typi-

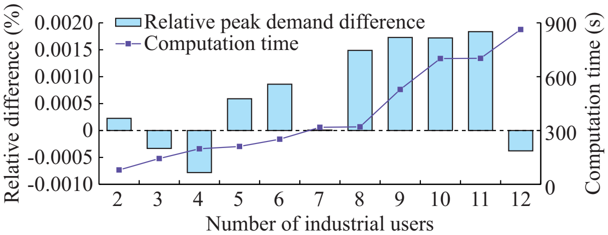

Fig. 8. Changes of relative peak demand difference and computation time with different numbers of industrial users for ADMM-based decentralized approach.

cal days. This demonstrates the capability of our proposed model in dealing with more typical days. In addition, Fig. 7 also shows that the demand management model gives the same result of electricity peak demand (20.949 MW) for different numbers of typical days. Increasing the number of typical days would not further improve the accuracy of peak demand calculation. This is because the optimal peak demand is mainly determined by the peak-load typical day, instead of the number of typical days. Considering that the peak demand is the most important output of our proposed demand management model, which would be used to calculate the peak demand charge, it is reasonable to select four typical days in this case to achieve favorable computation performance.

Figure 8 illustrates the changes of relative peak demand difference between the centralized approach presented in Section II-B and ADMM-based decentralized approach presented in Section III as well as the computation time of the decentralized approach with different numbers of industrial users. It can be observed that the proposed decentralized approach can obtain high-quality solutions of peak demand for all cases from two to twelve industrial users within 900 s. The relative difference of peak demand between centralized and decentralized approaches is always smaller than 0.002%. Therefore, our ADMM-based decentralized approach can scale well for a large number of industrial users.

V. Conclusion

Under the TPT policy, this paper develops a decentralized industrial park demand management approach considering the IDR of CHP units and centralized thermal storage. The centralized demand management model for industrial park with CHP units and thermal storage is firstly proposed, which is built on an AC power flow of electrical distribution network via the SOCP formulation. The heat dissipation of thermal storage as well as thermal delay effect and heat losses of heat pipelines is considered in the proposed model. Then, the proposed model is computed by the ADMM algorithm in a distributed manner to protect private data of all participants while deriving solutions with high quality.

Numerical results validate the effectiveness of our proposed demand management approach. Specifically, through the IDR of CHP units, both peak electricity demand and the electricity power purchased from the utility decrease significantly, leading to noticeable savings in both peak demand charge and electricity energy charge for industrial park. After involving the centralized thermal storage, the total energy bill of industrial park further decreases, because thermal storage efficiently utilizes the waste heat and increases the flexibility of CHP units. Finally, the ADMM-based decentralized approach can provide the same optimal results of demand management as the centralized approach, while presenting smaller volume of data exchange.

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