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Low Carbon Demand Response for Industrial Loads Considering Production Characteristics

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***Abstract*—Industrial loads present significant potential as demand response resources for enhancing the regulation flexibility of power systems. However, their unique production characteristics and low carbon emissions pose critical challenges to fully exploiting this potential. To address these challenges, this paper proposes a low-carbon demand response dispatch strategy tailored to industrial loads, considering their specific production characteristics. First, we summarize these production characteristics as minimum operation supply, minimum operation period, and coupled operation requirements. Next, we introduce dynamic carbon emission factors to capture real-time emission intensity. Based on this, we formulate an optimization model for low-carbon demand response that coordinates industrial loads to provide regulation capacities while satisfying their production needs and minimizing carbon emissions. Finally, case studies using realistic industrial load data demonstrate the advantages of the proposed method in enhancing demand response effectiveness and reducing carbon emissions.**

***Keywords*—demand response, carbon emission reduction, industrial loads, production characteristics**

I. Introduction

Under the ambitious goals of carbon peaking and carbon neutrality presented by the government of China, the penetration of renewable energy sources (RESs) is increasing dramatically in recent years [1]. Nevertheless, their inherent output uncertainties pose significant challenges to the real-time supply-demand balance of power systems [2]. Worse still, multiple extreme weather, such as the cold wave and extreme heat, occurred more frequently all over the world, leading to explosive growth of electricity consumption within a short period [3]. In China, the supply-demand imbalance is expected to increasingly expand in some provinces, e.g., the forecast electricity shortage in Zhejiang will exceed 26 billion kWh in 2025 [4]. Because of the full utilization of conventional generation resources, exploiting the regulation potential at the demand side is a powerful approach to address these short-term supply-demand imbalances [5].

To avoid arbitrary load-shedding, demand response (DR) programs are designed to explore the regulation potential of various flexible resources. Industrial loads are regarded as promising flexible resources due to their dramatic electricity consumption, which accounted for about 54% of total usage in 2020 [6]. Compared with residential and commercial loads, industrial loads have several advantages: *i*) significant regulation capacity; *ii*) non-distinctive seasonal characteristics; and *iii*) high-level automation [7]. These advantages make the industrial loads participate in DR more easily with reliable regulation capacities. In this light, under most electricity shortage conditions, industrial loads are always the first choice to be responsible for load-shedding. For instance, many factories are required to stop to guarantee the energy supply to residents in China in 2022, when there are serious electricity shortages caused by extremely hot weather [8]. However, such an arbitrary DR adversely affected the basic manufacturing processes of industrial loads.

Most demand side management usually concentrates on the DR capacity allocation [9], [10], while ignoring the unique production characteristics of industrial loads. To be specific, industrial loads consist of first-level loads and security loads, whose power supply must be guaranteed during operation. Moreover, production processes of industrial loads have typical periodical features, meaning that the power supply should be continuous before finishing the current production period. In[6], the energy district supply systems with the process industry loads are explored to provide more flexibility for renewable energy fluctuations. Ref. [11] proposed an optimization method to explore the coupling features of industrial integrated energy, so as to provide DR capacity. Most existing research only took the inner production characteristics of industrial loads into consideration. Nevertheless, coupled operation requirements among different industrial loads usually were ignored, especially for an industrial park with lots of factories.

Despite the DR provision, carbon emission reduction is also emphasized repeatedly. Ref. [12] designed the low carbon demand response (LCDR) mechanism and analyzed the corresponding benefits based on carbon emission flow. The low carbon dispatch of the distribution network was proposed in [13] to handle the uncertainties of high penetration of photovoltaics considering DR. Previous researchers mainly concentrated on residential or commercial users. As significant electricity consumers, industrial loads have emitted large carbon dioxides and are confronting rigorous situations of carbon emission reduction. Therefore, it is of great importance to further explore the LCDR dispatch for industrial loads, contributing to carbon reduction in industrial sector.

To address these research gaps, the LCDR dispatch is proposed in this paper for industrial loads considering their unique production characteristics. The main contributions are summarized as follows:

1) The unique production characteristics of industrial loads are accounted for, including minimum power supply, minimum operation period, and coupled operation requirements. On this basis, the DR coordination is proposed to provide regulation capacities for power systems with the aim of minimizing adverse impacts on the production of industrial loads.

2) Introducing the dynamic carbon emission factor (DCEF) into the LCDR dispatch problem, so as to optimize the DR provision of industrial loads with respect to the carbon emission intensity variation during the DR period and satisfy their expectation on carbon emission reduction.

The remainder of this paper is organized as follows: Section II introduces the LCDR coordination framework for different industrial loads, accompanied by their production characteristics. The LCDR is formulated as an optimization problem in Section III, so as to reduce carbon emissions when providing DR capacities. The case studies are conducted in Section IV. Finally, the main conclusions are summarized in Section V.

II. LCDR OF INDUSTRIAL LOADS

A. LCDR Coordination Framework for Industrial Loads

As the large consumer, lots of industrial loads can participate in the DR program alone, however, the potential coordination among different industrial loads is difficult to achieve to satisfy personalized requirements. To overcome this shortcoming, the load aggregator is usually involved to play an important role between power systems and various N industrial loads, as shown in Fig. 1.

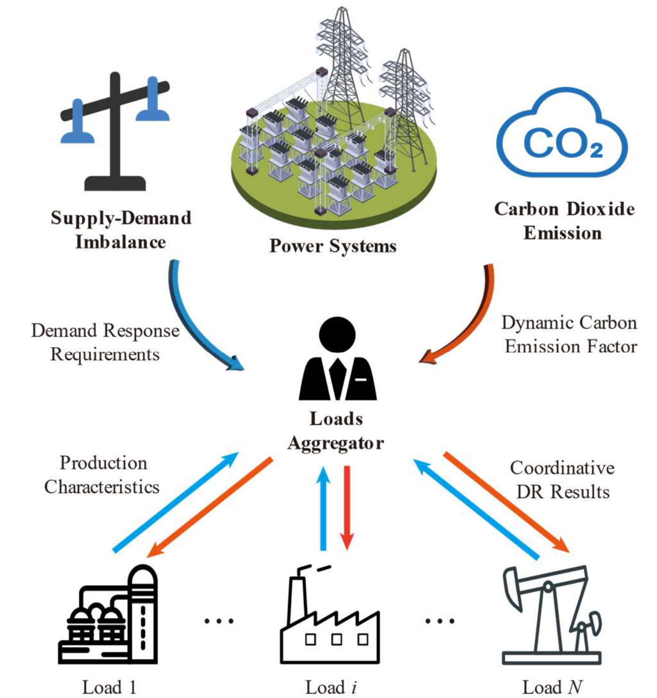

Fig. 1 The DR framework for industrial loads

It should be noted that these aggregated industrial loads need to be located within a physical region, e.g., the same distribution network. On the one hand, their carbon intensity derived from electricity consumption is similar and can be calculated according to the DCEF from the real-time carbon flow results. On the other hand, the mutual production influence among industrial loads can be taken into consideration, such as the coupled operation requirements.

When there are supply-demand mismatch risks, power systems will release specific DR requirements to the aggregator in advance, including specific time-varying power profiles and acceptable fluctuation regions during the DR period. In order to minimize the DR effects on normal production, industrial loads need to submit their electricity usage requirements to the aggregator before implementing DR, e.g., minimum power supply, minimum operation period, and coupled operation requirements. Meanwhile, the DCEF during the DR period can be forecasted by the aggregator according to historical data, so as to guide the following LCDR dispatch.

Finally, the load aggregator will optimize and allocate the DR capacities coordinately to maximize the total power supply and minimize carbon emissions of industrial loads.

B. Production Characteristics of Industrial Loads

Different from residential and commercial loads, industrial loads possess their unique electricity consumption requirements due to production or safety, which are summarized as following three aspects:

1) Minimum Power Supply

During the production process, the first level loads and security loads are extremely important, whose electricity demands must be guaranteed when operating, namely minimum power supply [14].

Taking the aluminum electrolysis industry as an example, the electrolyzers belong to the first-level loads because their supply reliability has significant impacts on lifespan and safety. Besides, different industrial loads have different minimum power supply. To be specific, the minimum power supply of aluminum electrolysis accounts for nearly 95% of total power, while that of food manufacturing is about 35%. As shown in Fig. 2, the dot-dashed blue and orange lines illustrate the different minimum power supplies of industrial loads i, j, respectively. Hence, the load aggregator should allocate the appropriate DR capacity with respect to their minimum power supply requirements.

2) Minimum Operation Period

Most production processes are periodical, meaning that the electricity supply should satisfy the minimum operation period, so as to finish a complete production process.

In terms of cement production, its process can be divided into 4 main subprocesses, including crushing, kiln feed preparation, clinker production, and finish grinding [15]. Every subprocess has a specific production period, the electricity supply should be satisfied to avoid affecting production quality. As shown in Fig. 2, the industrial load should continue to consume electricity for a specific period after startup, then the factory is allowed to stop operating.

3) Coupled Operation Requirements

Apart from the inner production characteristics, the mutual influence among different industrial loads, namely coupled operation requirements, can never be ignored. Specifically, the coupled operation requirements usually exist within the production chains, where the production variations of upstream enterprises will lead to similar variations of the downstream enterprises.

For instance, the whole battery production chain consists of several processes, i.e., the battery cell production and the battery cell package, which are coordinately finished by different enterprises. The products of upstream enterprises are exactly the raw materials of downstream enterprises, so the production variations will spread to the whole production chain. Assuming that the industrial loads i, j in Fig. 2 are coupled enterprises, it can be seen the electricity consumption of the industrial load j is synchronous with industrial load i with a constant delay τ_{ij}. In this light, their coupled characteristics need to be accounted for when optimizing DR participation.

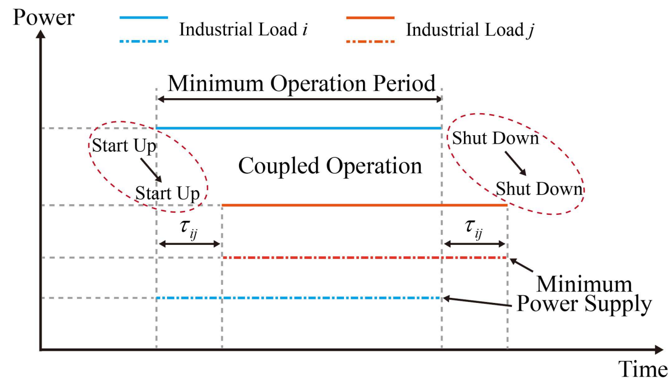

Fig. 2 Production characteristics of industrial loads

III. LCDR Dispatch Problem Formulation

A. LCDR Dispatch Objective

The LCDR dispatch aims to maximize the cumulative electricity consumption and minimize the carbon emission of industrial loads.

$$\max \sum_{t \in \mathrm{T}} \sum_{i \in \mathrm{I}} (EC_i^t - CE_i^t) \tag{1}$$

1) Energy Consumption: The energy consumption is the cumulative electricity consumption of total industrial loads. Industrial users always tend to consume more electricity to increase production and profits within the DR requirements.

$$EC_i^t = s_i^t P_i^t \tag{2}$$

where s_i^t is the 0-1 variable used to indicate the operating states of i-th load at time t; P_i^t mirrors the power of i-th industrial load at time t.

2) Carbon Emission: The carbon emission indicates the indirect carbon emission of industrial loads by consuming electricity, which can be calculated in response to DCEF and the corresponding power:

$$CE_i^t = \eta \lambda_{CEF}^t s_i^t P_i^t \tag{3}$$

where η mirrors the parameter to evaluate the value of carbon emission; λ_{CEF}^t represents the DCEF at time t.

B. LCDR Constraints

1) Demand Response Constraints: During the whole DR period, the cumulative electricity consumption should be less than the required maximum electricity consumption. Despite the energy balance, the total operating power also needs to be restricted to preset intervals.

$$\sum_{t \in \mathrm{T}} \sum_{i \in \mathrm{I}} EC_i^t \leq E_{DR} \tag{4}$$

$$(1-\alpha) P_{DR}^t \leq \sum_{i \in \mathrm{I}} P_i^t \leq (1+\alpha) P_{DR}^t \tag{5}$$

where P_{DR}^t and E_{DR} represent the required maximum operating power and electricity consumption during the DR period, respectively. T and I are the sets of optimization timesteps and industrial loads, respectively. Equation (5) restricts that the total power cannot violate the acceptable regions, otherwise, the situation may occur that the most DR behaviors distribute at a short period but the cumulative electricity consumption satisfies requirements. The acceptable regions are defined by the maximum power fluctuation rate α.

2) Power Supply Constraint: The operating power of industrial loads should be restricted within the minimum power supply and the rated power:

$$s_i^t P_i^{\min} \le P_i^t \le s_i^t P_i^{\max} \tag{6}$$

where $P_i^{\min}$ and $P_i^{\max}$ indicate the minimum and maximum operating power of i-th industrial load, respectively.

3) Power Adjustment Constraint: The power adjustments of industrial loads between two continuous timesteps cannot exceed the physical constraints of equipment:

$$\left|P_i^t - P_i^{t-1}\right| \le \Delta P_i^{\max} \tag{7}$$

where $\Delta P_i^{\max}$ indicates the maximum power adjustment during a timestep.

4) Minimum Operation Period Constraints: The electricity consumption of industrial loads should satisfy the minimum operation period. Besides, the minimum closing period is also added to prevent frequent startup and shutdown procedures:

$$\sum_{t}^{t+T_{on,i}^{\min}-1} s_i^t \ge T_{on,i}^{\min}(s_i^t - s_i^{t-1}),\, t \in [1, t_{end} - T_{on,i}^{\min} + 1] \tag{8}$$

$$s_i^t \ge s_i^t - s_i^{t-1},\, \forall t \in [t_{end} - T_{on,i}^{\min} + 2, t_{end}] \tag{9}$$

$$\sum_{t}^{t+T_{off,i}^{\min}-1} (1 - s_i^t) \ge T_{off,i}^{\min}(s_i^{t-1} - s_i^t),\, t \in [1, t_{end} - T_{off,i}^{\min} + 1] \tag{10}$$

$$1 - s_i^t \ge s_i^{t-1} - s_i^t,\, \forall t \in [t_{end} - T_{off,i}^{\min} + 2, t_{end}] \tag{11}$$

where $T_{on,i}^{\min}$ and $T_{off,i}^{\min}$ are the minimum operating and closing periods of i-th industrial loads, respectively. t_{end} is the last timestep of T.

5) Coupled Operation Constraint: The industrial loads with coupled operation requirements should have similar operating periods:

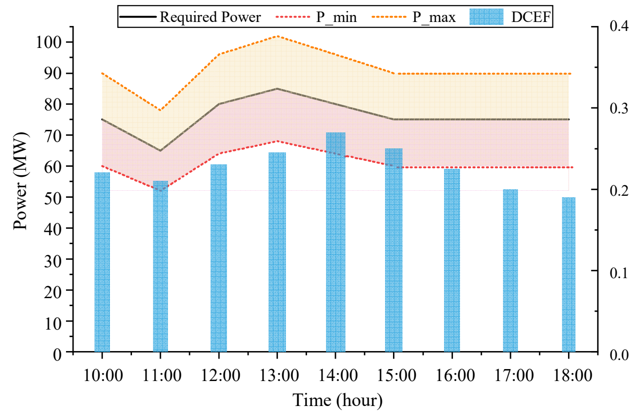

Fig. 3 The required DR power and the DCEF profiles

$$s_i^t - s_j^{t+\tau_{ij}} = 0, i, j \in \mathrm{I}_c, t \in \mathrm{T} \tag{12}$$

where τ_{ij} indicates the delay time of coupled operation. $\tau_{ij} = 0$ represents these loads are synchronously coupled, and $\tau_{ij} > 0$ represents they are asynchronously coupled. I_c is the set of industrial loads with coupled operation requirements.

The above LCDR dispatch can be formulated as a mixed integer optimization problem and efficiently solved by commercial solvers such as GUROBI.

IV. Case Study

A. Simulation Parameters

Based on the realistic data coming from an industrial park with 29 industrial loads in China, simulations on LCDR for industrial loads are conducted in this section. Firstly, the DR period is set as 10:00-17:00 with 8 hours. The detailed energy consumption of industrial loads is shown in TABLE I, including the initial operating power p_i^{init}, the minimum and maximum operating power $p_i^{\min}$ and $p_i^{\max}$, the maximum power adjustment $\Delta P_i^{\max}$, and the minimum operation period $T_{on,i}^{\min}$. The industrial loads 16 and 17 have coupled operation requirements with 1-hour delay, and loads 18 and 23 have instantaneous coupled operation requirements.

In terms of the industrial load aggregator, the maximum energy consumption during the DR period is set as 610MWh, and the time-varying power profiles are shown in Fig. 3. The

TABLE I The detailed energy consumption of industrial loads

Loads	P_i^{init}	$P_i^{\min}$	$P_i^{\max}$	$\Delta P_i^{\max}$	$T_{on,i}^{\min}$	Loads	P_i^{init}	$P_i^{\min}$	$P_i^{\max}$	$\Delta P_i^{\max}$	$T_{on,i}^{\min}$	Loads	P_i^{init}	$P_i^{\min}$	$P_i^{\max}$	$\Delta P_i^{\max}$	$T_{on,i}^{\min}$
1	187.5	20	200	1000	5	11	269.72	113	1130	1000	0	21	2142.27	320	3200	2000	0
2	32.04	31.5	315	1000	2	12	558.6	180	1800	2000	0	22	788.54	600	6000	4000	2
3	31.48	25	250	1000	2	13	167.3	160	1600	1000	0	23	3872.33	1000	4000	3000	0
4	259.34	63	630	1000	0	14	1291.15	160	1600	1000	3	24	3346.53	450	4500	3000	2
5	124.7	63	630	1000	0	15	1472.99	200	2000	2000	0	25	980.6	450	4500	3000	0
6	956.34	100	1000	1000	3	16	431.63	200	2000	2000	0	26	4458.39	600	6000	4000	0
7	172.8	100	1000	1000	3	17	529.79	400	4000	3000	2	27	1106.7	1200	12000	6000	2
8	674.8	600	1000	1000	3	18	953.33	250	2500	2000	0	28	8954.6	945	9450	6000	0
9	687.49	625	1250	1000	0	19	1207.33	250	2500	2000	2	29	1562.29	1170	11700	8000	0
10	109.8	100	1000	1000	0	20	354.24	325	3250	2000	2	\	\	\	\	\	\
Units	kW			kW/h	h	Units	kW			kW/h	hour	Units	kW			kW/h	hour

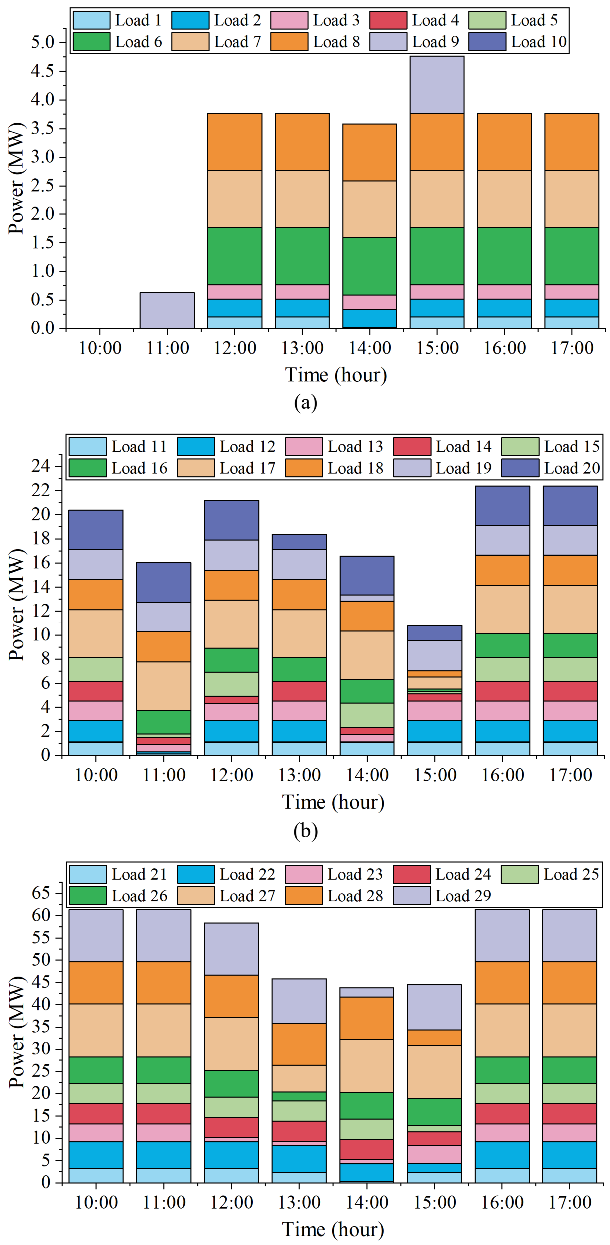

Fig. 5 The LCDR dispatch results of industrial loads: (a) loads 1-10; (b) loads 11-20; (c) loads 21-29.

required operating power during the DR period is represented by the black solid line. The acceptable power fluctuations regions consisting of upward and downward intervals are indicated by the yellow and pink areas, respectively. Besides, the predicted DCEFs revealing the real-time carbon emission intensity are represented by the blue columns [12].

B. Simulation Results

Upon receiving the DR requirements from power systems, the aggregator needs to optimize the affiliated industrial loads based on their production characteristics and the DCEFs. The specific LCDR dispatch results are shown in Fig. 5.

Firstly, the proposed LCDR dispatch can guarantee the

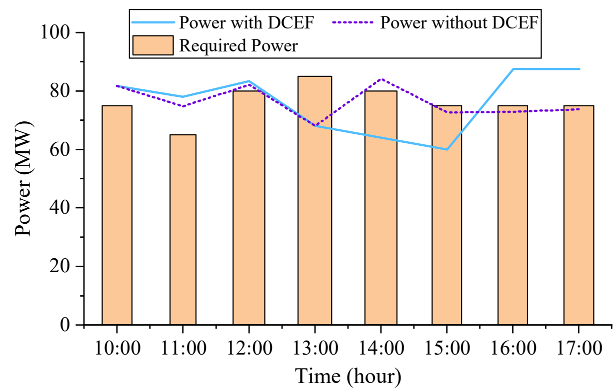

Fig. 4 The effects of the DCEF on DR profiles.

minimum power supply of industrial loads. For instance, loads 8, 9, and 23 have relatively higher requirements, whose values are 600kW, 625kW, and 1000kW. Their electricity supplies have been completely satisfied to maintain the stable operation of the first-level and safety loads.

Then, the minimum operation periods during the production processes are also taken into consideration. To be specific, loads 1, 2, and 3 have the minimum operation period requirement of 5 hours, 2 hours, and 2 hours, respectively. After the LCDR dispatch, all of them are arranged to operate from 12:00 to 17:00 as shown in Fig. 5 (a), the realistic operating hours have reached 6 hours.

Moreover, the coupled operation requirement is also one of the most important production characteristics among industrial loads. In terms of loads 16 and 17 that have delayed coupled operation, load 17 starts up 1 hour later after load 16 begins to operate at 10:00, as shown in Fig. 5 (b). During the remaining periods, both of them simultaneously keep operating. Besides, loads 18 and 23 are instantaneous coupled pairs, so they need to start up and shut down at the same time. As shown in Fig. 5 (b) and (c), loads 18 and 23 are operating for the whole DR period and satisfy the coupled operation.

TABLE II The carbon emissions and electricity usage of LCDR and DR.

	Carbon emission (tCO_2)	Electricity usage (MWh)
LCDR	139.64	610
DR	141.25	610

Compared with conventional DR dispatch, the proposed LCDR dispatch takes the carbon emission reduction into consideration, the power profiles with and without DCEFs are indicated by the solid blue line and dotted purple line in Fig. 4, respectively. Generally speaking, involving carbon emission reduction tends to transfer the electricity usage from the period with the higher DCEF to that with the lower DCEF. For clarity, the industrial loads reduce energy consumption from 13:00 to 15:00, while increase electricity usage in other periods. However, due to the constraints on DR power and production characteristics, the electricity consumption cannot be transferred during the period with the lowest carbon emission. In fact, the power profiles are various within the feasible regions.

Finally, the carbon emissions and electricity usage of LCDR and DR are analyzed, respectively, their results are shown in TABLE II. The electricity usage of LCDR and DR is 610MWh because industrial loads always want to consume more energy to earn extra profits. For the carbon emission, the proposed LCDR has reduced 1.61 tCO_2, proving its advantages in carbon emission reduction.

V. Conclusion

Industrial loads are promising resources to enhance the regulation flexibility of power systems with high penetration of RESs. This paper proposed the LCDR dispatch to coordinate different industrial loads to provide regulation capacities. Firstly, the production characteristics of industrial loads are summarized as minimum power supply, minimum operation period, and coupled operation requirements, which are involved in the LCDR dispatch to satisfy their energy consumption. Then, in order to achieve their expectation of carbon emission reduction, the DCEF is introduced in the LCDR optimization problem, guiding the energy consumption transfer from the period with higher emission to that of lower emission. Lastly, case studies are conducted based on the realistic data of industrial loads, proving the effectiveness of the proposed LCDR on production satisfaction and carbon emission reduction.

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