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Low-carbon benefits analysis of energy-intensive industrial demand response resources for ancillary services

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Abstract As a major CO_2 emission source, the low-carbon development of the power sector requires the sector's own efforts and the cooperation with other industries, especially in the context of rapid development of renewable generation technologies. The industrial demand response resources (IDRR) will be helpful to improve wind power penetration and bring low-carbon benefits if they are utilized to provide ancillary services (AS) for the power system. In this paper, demand response (DR) characteristics of industrial users are firstly analyzed according to their production process and electricity consumption distribution. In order to have an in-depth study of the response mechanism of industrial loads to provide AS, cement and aluminum smelter are selected as two typical IDRR, and the AS type they provided and response mechanism are analyzed. Based on the data of these two industries in certain provinces of China, low-carbon benefits considering IDRR to provide AS are analyzed.

Keywords Demand response (DR), Ancillary services (AS), Energy-intensive industrial users, Low-carbon benefits

1 Introduction

As a large developing country, China is facing the pressure of promoting economic growth while saving energy resources as well as protecting the environment. Given that China is the world's largest carbon emitter [1], the government has announced to reduce its carbon emission intensity by 40%–45% by 2020 compared to that in 2005. As the important link in the chain of energy industry, the power sector should actively explore low-carbon development ways that are conducive to long-term interests. And power sector decarbonization is an important component of the low-carbon development of energy-intensive industries.

Renewable energy technologies have been considered as a key factor for promoting the power sector decarbonization [2]. The Renewable Energy Law promulgated by the government was put into effect on January 1, 2006, according to which, grid enterprises are required to buy all the power produced by renewable energy generators [3]. As a result, China's renewable generation has experienced a rapid development in terms of both installed capacity and generation in past few years, but the problem of wind power penetration has become more serious and aroused continuous concern [4]. Generally, wind feed-in is unresponsive to system demand and is associated with a high level of uncertainty due to the volatile nature of wind [5]. It is different from the majority of thermal generation, which provides not only schedulable energy but also vital control services necessary to maintain the integrity of the power system [6]. With existing dispatching practices, different kinds of AS are provided by thermal generation, which has slow response speed and restricted ramp rates. Consequently, the thermal generation cannot operate with the optimum efficiency and causes significant carbon emissions and energy wastage. Under the background of power sector decarbonization, the real-time AS is increasingly needed. If the AS is all provided by thermal generation running part-loaded, it will not only reduce the efficiency of system operation, but also significantly undermine the

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system ability for absorbing intermittent renewable output [7], which will result in increasing pressure of energy conservation and emission reduction.

From the perspective of energy-intensive industries, the government regulation is mainly adopted in Chinese AS fields and the main measure is power rationing. This kind of load management mode is simple and extensive, thus it has limited effects on low-carbon development and industrial structure adjustment. The proportion of iron and steel, building materials, colored metals and other energy-intensive industries in Chinese power consumption is relatively high. Exploring the potential of energy-intensive industries to provide AS can not only relieve the energy wastage brought about by disordered development, but also supplement the shortage of reserve resources caused by the rapid development of renewable energy.

Smart grid realizes the real-time interaction between power sector and other sectors on the basis of modern technologies of information, communication, sensor and control. It enables DR to another interaction resource with considerable potential apart from the thermal generation [8]. With the development and improvement of demand side management technology, users can response to remote control or price signal quickly and automatically, and have a technical advantage in terms of speed and response accuracy. Likewise, they have advantages in response costs and the feasibility in providing AS from the technical perspective [9]. Therefore, it is a new topic in the AS field to research the DR actively participating AS and explore the mechanism of operation design.

This paper is organized as follows: Section 2 describes several kinds of AS and analyses the characteristics and low-carbon benefit of industrial DR resources. In section 3, by choosing cement and aluminum smelter as two typical IDRR, the response mechanism of these two industries is established considering their own production process. In section 4, two different scenarios, in which the DR potential of industrial users is fulfilled or not, are developed and low-carbon benefits are analyzed based on the industry data of certain province in China. Finally, some conclusions are shown in section 5.

2 IDRR for AS ancillary services

2.1 Ancillary services

Although AS include both real and reactive power applications, and their classifications are quite different according to different research view. This paper focuses only on real power AS and concerns main contents as follows [10, 11].

1) Regulation: It requires continuous response to short-term load fluctuation (including regulation up/down). Some loads may be capable of supplying regulation considering their fundamental capabilities.
2) Spinning reserve: It responses to unplanned load increase or decrease (mainly provided by the unit in the running state).
3) Non-spinning reserve: It responses to sudden but infrequent disruptions (mainly provided by the off-grid unit that can start up at any time without maintenance plan). Generally, some responsive loads are allowed to supply non-spinning reserve.

The three types of AS can also be distinguished through their physical parameters. Fig. 1 plots the response speed and duration on the horizontal axis and advance notice on the vertical. For example, if load i wants to provide non-spinning reserve, it must satisfy the following standards:

$$\begin{cases} T_{\mathrm{an}\_i} \le t_3 \\ T_{\mathrm{rs}\_i} \le t_1 \\ T_{\mathrm{rd}\_i} \ge t_2 - t_1 \end{cases} \tag{1}$$

where T_{an_i} is the advance notice time of load i; T_{rs_i} the response speed of load i; T_{rd_i} the single response duration of load i; t_1 the slowest acceptable response speed after load received the signal; t_3 the maximum acceptable advance notice time; and $t_2 - t_1$ the shortest acceptable response duration.

For different DR resources, there are differences in advance notice time. Generally, industrial users may require 2 to 4 hours of advanced notice to prepare. Other load types, such as commercial buildings, may not need it in general [12]. Longer response duration is more useful for grid operators, which could be applied to most periods. Response speed is a strict parameter and there is no difference for all users.

2.2 Industrial demand response resources

In recent decades, especially after 2002, the proportion of industrial electricity consumption has maintained a sustained upward trend [13]. Considering electricity price

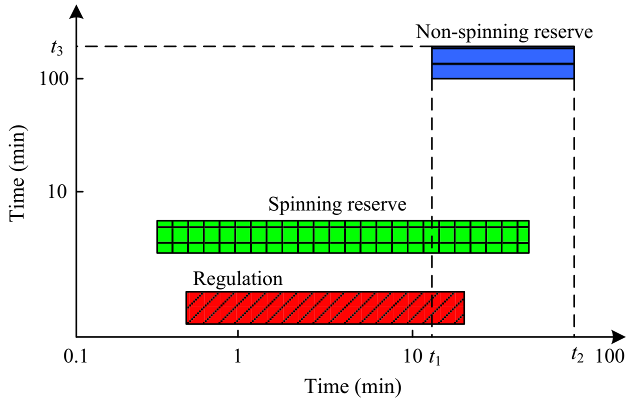

Fig. 1 Advance notice, response speed and duration of AS

as the main cost of these energy-intensive industries, power sector should participate more in building low-carbon development mode and promoting industrial upgrading. A specific DR program for these industries is necessary in the long term.

DR has been traditionally defined as a set of time dependent activities that reduce, shed or shift electricity use to improve electric grid reliability and manage costs, which mainly relies on customers' motivation for reducing electricity tariff [14]. For AS, technical requirements are more challenging in terms of speed and accuracy when compared with traditional DR. Specifically, DR for AS is needed year-round and not just for peak hours [15]. Different works have been presented in the past in order to evaluate DR for AS in different sectors. Lawrence Berkeley National Laboratory has carried out a lot of research about DR for AS under the framework of smart grid and verified a series of power loads which have the ability to provide AS by experiment and demonstration project, such as lighting, air conditioning, refrigeration, data center and water pumping, etc [16–21]. Reference [22] examined the characteristics of cement plants and their ability to shed or shift load to participate in DR. Reference [23] identified that six hours of load shifting could be achieved without adversely affecting production at a South African cement plant. Reference [24, 25] investigated the available opportunities of one aluminum smelter factory in AS market and discussed the regulation service that electrolytic aluminum enterprises could provide. Reference [26] analyzed the flexibility potential of customers in one meat industry based on the management of the most energy consuming process in this type of segment: cooling production and distribution, which is one of the most representative sectors in Spain. Reference [27] briefly estimated the technical and economic potential of energy-intensive industries to provide demand side management in electricity and balance markets through 2030, including chloralkali process, mechanical wood pulp production, aluminum electrolysis, electric arc furnace, cement mills. However, all the aforementioned analyses are limited in that they are case studies for a single industrial plant or sector, and they have not investigated the economic influence and low-carbon benefit of IDRR for AS through day-ahead optimizing dispatching.

In recent years, public attention on DR has been directed mostly to the residential sector due to the rapid development of smart meters and smart homes. But industry sector has a much larger consumption footprint and peak load contribution, and in some respects is well advanced in the implementation of smart grid technologies [28]. It is noteworthy that industrial users' loads have greater potential for optimization, and they show strong interest in the management of power use for price benefits.

According to the industry category, DR resources have different kinds of types. As shown in Fig. 2, unlike thermal generation, the ability of DR to provide AS is definitely affected by a serious of external variables, especially for commerce and inhabitant users. However, the majority of industrial users are flow industry and the production must keep flowing. Compared with commerce and inhabitant users, IDRR have the following advantages.

1) Large capacity: Industrial users are large consumers. Peak loads can reach hundreds of megawatt, and annual consumptions can reach hundreds of millions of kilowatt-hour. However, other power consumers require additional mechanisms, such as aggregator, because their power level is negligible.
2) High load rate: The difference of industrial users' peak and off-peak load usually keep in a low level, which can fit well with the output fluctuation of wind farm and benefit for power system stability.
3) Climate insensitive: A factory's electricity consumption bears little relationship to the cycle of the seasons.
4) Easy to manage: Modern factories are highly automatic and can meet the requirements of providing AS by a simple modification.

2.3 Low-carbon benefit of industrial users to provide AS

The source of low carbon benefits from smart DR can be concluded as follows.

1) Reduce the frequent ramp up/down of the unit. In current situation, thermal generation undertakes the primary mission to provide AS, which will result in huge accounts of ramp up/down costs and extra carbon emissions. Some units must operate in uneconomic range in case a unit or a transmission line unexpectedly fails. If controlled responsive loads could provide AS in the situation of meeting criteria, especially for some industrial users which could perfectly follow AS

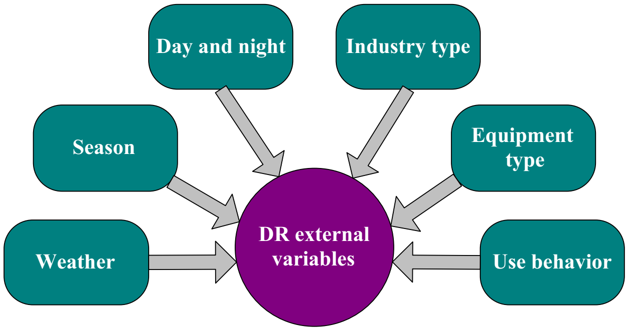

Fig. 2 DR external variables

commands, it will reduce the power system requirements for AS and lead to a large cut-in carbon emissions.

2) Improve the penetration of renewable energy resources. Under the traditional dispatching mode, we choose to adjust thermal power output to deal with the randomicity of wind farm. If there are more responsive loads, which could adjust their production process to fit the wind output characteristics, the construction requirement of thermal power for providing AS will be reduced significantly. This will also improve the penetration of wind power and make low-carbon benefits.

3 Response mechanism of typical industrial users for AS

3.1 Cement

The proportion of electricity bill in the total cost of cement enterprise is about 30%. In recent years, the production pressure of cement enterprise has been decreasing as a result of economic situation and industrial restructuring. The flexibility of participating in DR is improved. During the production process, just the kiln must keep running. The operating time of raw mill, coal mill and cement mill can be adjusted as needed. And these adjustable devices account for 60%–70% of the total electricity consumption of cement production. Generally, the production process and electricity consumption distribution of cement enterprise are shown in Fig. 3.

With the correlation between coal mill and kiln during production, it is not suitable to frequently start and stop coal mill [23]. Thus, raw mill and cement mill are the optimal non-spinning reserve resources of cement enterprise. The storage amount at various points in the cement process has the minimum storage capacity during the producing process, which determines the maximum response duration of all types of devices. Using raw mill as an example, on account of the good uniformity of raw meal quality, the remaining storage of raw meal should not be too low. When the storage is lower than a certain proportion, it will lead to the reduction of product quality if the raw mill participants in AS.

It is assumed that the load curve of mill j usually has a flat shape $P_{\text{base\_}j}$ as shown in Fig. 4. In the case of providing AS, the daily load curve of mill j can be expressed as $P_{\text{ns\_}j}$. For simplicity, we suppose the production decision satisfies the following conditions:

$$E_{\text{ns\_}j} - (E_{1\_j} + E_{2\_j}) = 0 \tag{2}$$

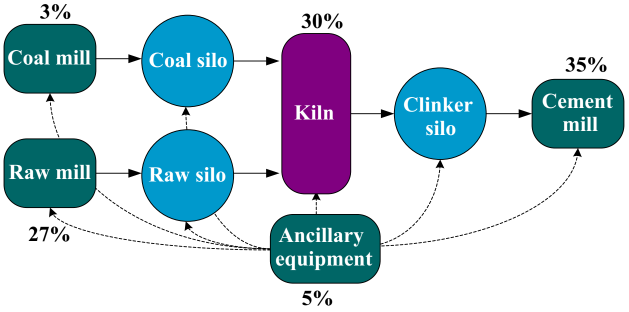

Fig. 3 Production process and electricity consumption distribution of cement enterprise [30]

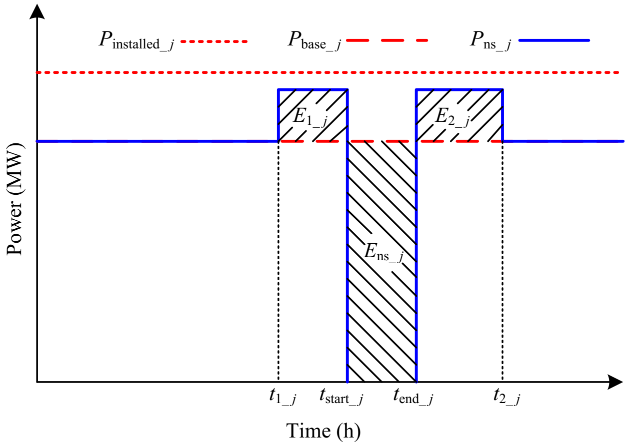

Fig. 4 The daily load curve of cement providing non-spinning reserve

where $E_{\text{ns\_}j}$ is the energy reduced during providing non-spinning reserve, and E_{1_j} and E_{2_j} are additional energy consumed before and after the non-spinning reserve respectively, which are used to maintain the relevant silo's input and output stability. It should be noted that the beginning and ending time of E_{1_j} and E_{2_j} could be adjusted according to power system's requirement without affecting the normal production of the premise.

Table 1 shows the technical parameters of production equipment in cement enterprise that is summarized based on different cement factories in China [29]. The flexibility of every process is expressed in the term of percentage, representing the proportion of one adjustable process in the installed capacity of cement enterprise.

Based on the above analyses, it is concluded that the large cement enterprises could provide greater flexibility because the storage space of raw silo and clinker silo are large enough to last for days. Therefore, responding to an AS event should have no impact on plant operation costs and productivity.

Table 1 Response parameters of various cement production equipments

	Flexibility (%)	Duration (h)	Times
Raw mill	16–20	1–3	1–2
Coal mill			
Cement mill	20–24	1–3	1–2
Kiln			

3.2 Aluminum smelter

Electrolytic aluminum is a key industry for energy saving. For a typical aluminum smelter, electric power accounts for 30% to 40% of the overall cost of producing primary aluminum. Compared with cement enterprise, it has fairly simple production process. Aluminum smelting pot is the core equipment in aluminum production and consumes the vast majority of energy. Thus the analysis of DR potential in an aluminum smelter is mainly focused on the pot line.

Aluminum smelting pot, which is electronically controlled, could potentially follow automatic generation control commands accurately [24]. Adjusting the incoming voltage could control the power consumption of each pot. Thermal balance is very important for the pot operation. It is maintained by controlling the energy input to the pot. Existing smelting plants can provide AS in two ways.

1) Adjust input voltage. As long as the smelting process is stable, reducing or increasing the input voltage of pot, thereby reducing or increasing electricity consumption, may achieve fast response. This action can be precisely achieved within seconds.
2) Turn the entire pot line off. A pot can provide AS by turning the entire pot off, thereby reducing the electricity consumption by a larger amount. In that case, the duration of an interruption is more critical and can be sustained only for short periods, depending upon the specific plant limitations.

In this paper, we just choose the way of adjusting input voltage, which was proved to be feasible [25].

As shown in Fig. 5, P_r and P_{base} represent the daily load curve of a pot with and without providing AS respectively. Regulation up and down could be regarded as two services to power system, but we assume that the up and down adjusting range should be consistent for convenience. In a dispatching cycle, regulation up and down are required to be equal, as in (3).

$$\sum E_{ru} - \sum E_{rd} = 0 \tag{3}$$

where E_{ru} is the energy consumed for providing regulation up, and E_{rd} is the energy consumed for providing regulation down.

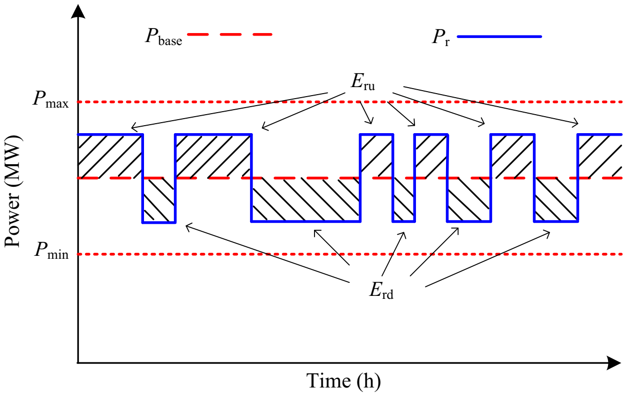

Fig. 5 The daily load curve of aluminum smelter providing regulation service

Table 2 The response parameters of aluminum smelting pot

	Flexibility (%)	Duration (h)	Times
Aluminum smelting pot	≤3	≤12	Continuously

Table 2 summarizes the response parameters of aluminum smelting pot. The flexibility of aluminum smelting pot is defined as the proportion of adjustable load in one pot. The dispatching cycle is one day so that the duration of provide regulation up or down must be no more than 12 hours.

As discussed above, regulation up and regulation down are required to be equal to reduce the impacts on product quality, process and productivity. Compared with small aluminum smelter enterprises, large aluminum smelter enterprises that have self-generation power plants will have obvious advantages in regulation response flexibility.

4 Scenario results

On basis of the analytical treatise above, we use data of cement and electrolytic aluminum industries in certain province of China to analysis the low-carbon benefits of IDRR. The basic data of these two industries is shown in Table 3. Due to the difficult of obtaining complete load data, we choose the daily average load of typical days in different seasons (April 18, July 26, September 12 and December 19) as a reference.

The implementation of IDRR to provide AS is similar to power plant capacity in electricity production, which could be regarded as the substitution of thermal generation. Table 4 and 5 summarize the DR potential of these two energy-intensive industrial users.

Table 3 The basic data of cement and aluminum smelter industries in 2012

	Production (million tons)	Load level (MW)			
		Spring	Summer	Autumn	Winter
Cement	15386	3084	3080	2543	2884
Electrolytic aluminum	197	3264	3335	3276	3201

Table 4 Overview of the potential of cement for AS

	Process	Capacity (MW)	AS type	Utilization level (%)
Cement	Raw mill	522	Non-spinning	75
	Cement mill	638	Non-spinning	80

Table 5 Overview of the potential of aluminum smelter for AS

	Process	Capacity (MW)	AS type	Utilization level (%)
Aluminum smelter	Aluminum smelting pot	98	Regulation up/down	95

In order to preliminary estimate the low-carbon benefits of two typical energy-intensive industrial users, two scenarios are set as follows.

1) Scenario 1: The AS of power systems required is still provided by thermal generation, regardless of IDRR. We suppose that the obligation of different units is fixed and their CO_2 emission parameters are shown in Table 6.
2) Scenario 2: The IDRR are admitted into the AS market and the thermal generators keep running smoothly in the case of existing available IDRR. In scenario 2, two parameters, transforming factor τ and penetration factor λ, are introduced to simulate the potential change of energy-intensive industrial users for AS.

As shown in Fig. 6, transforming factor reflects the process of integration of energy-intensive industries, while penetration factor represents the acceptability of providing AS for power system. By comparing two scenarios, the low-carbon benefits of cement and electrolytic aluminum industries for AS are obtained in certain province of China from 2012 to 2020, as shown in Table 7.

Thus, it can be seen that IDRR can bring significant low-carbon benefits. But it is hard to be widely applied in most factories due to the acceptance of present period. Considering the increasing penetration of wind power and the potential of energy-intensive industrial users for AS, some traditional ideas should be gradually changed. Loads, especially industrial loads, could not focus on maintaining a flat curve on the premise of safety production. Flexible loads represent a significant and large resource for power sector.

Table 6 CO_2 emission intensity of different generators

	AS type	CO_2 emission intensity (kg/kWh)
Large generators	Regulation up/down	0.80
Small generators	Non-spinning	1.05

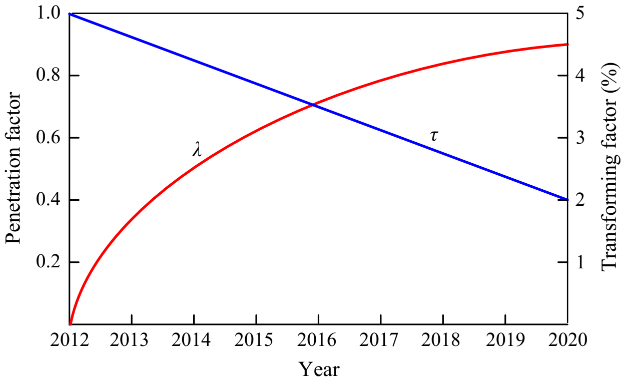

Fig. 6 Transforming factor and penetration factor

For the sake of economic interests, it is difficult to take the initiative to change the existing production mode for most enterprises. A relatively efficient incentive mechanism is essential. The existing response models that loads could participate in are mainly designed for peak load period, and there is still large gap between it and AS in terms of engagement standards and supervisor mode. Through the analysis of the response mechanism of cement

Table 7 CO_2 reduction volume

Year	CO_2 reduction volume (t)
2013	269.8×10^6
2014	354.2×10^6
2015	425.7×10^6
2016	465.5×10^6
2017	497.4×10^6
2018	516.0×10^6
2019	528.9×10^6
2020	555.3×10^6

and aluminum smelter enterprises, the incentive mechanisms of AS are put forward as follows.

1) Grid-industrial users: Grid could consider industrial users that have the ability to providing AS as power plants. Industrial users will get revenue according to real situation's requirements but not before they had been evaluated their qualifications. Besides, government regulators should give their additional subsidy for the low-carbon benefits they provide.
2) Generation-industrial users: On the basis of the geographical distribution and power supply business contact, all kinds of industrial users could form an AS alliance with related thermal generation separately. Then, industrial users could share the AS pressure and profits with generation. In this model, they also could earn additional subsidy for the low-carbon benefits.

5 Conclusions

This paper focuses on exploring the low-carbon benefits of energy-intensive industrial DR resources for AS. Cement and aluminum smelter are chosen as two typical IDRR for in-depth analysis. A preliminary calculation is carried out based on the response mechanism of cement and electrolytic aluminum. Then, the potential of CO_2 emission reduction of these two types of industrial users in certain province of China is revealed from 2012 to 2020. Due to the lack of related data, this paper could only present preliminary estimate. With the future development and improvement of DR technique, more attentions will be paid to industrial DR application.

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