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CHINA ELECTRIC POWER RESEARCH INSTITUTE

Unlocking Demand-Side Flexibility in China:

Current Status and Potential of Demand Response in the Industrial Sector

Report / December 2023

About RMI

RMI is an independent nonprofit, founded in 1982 as Rocky Mountain Institute, that transforms global energy systems through market-driven solutions to align with a 1.5°C future and secure a clean, prosperous, zero-carbon future for all. We work in the world's most critical geographies and engage businesses, policymakers, communities, and nongovernmental organizations to identify and scale energy system interventions that will cut greenhouse gas emissions at least 50 percent by 2030. RMI has offices in Basalt and Boulder, Colorado; New York City; Oakland, California; Washington, D.C.; and Beijing.

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Introduction

The power sector accounts for about 40% of global carbon emissions, and promoting the decarbonization of electricity production and the electrification of end-use consumption has become the consensus in the global response to climate change and the energy transition. The electrification of end-use consumption is a key measure to reduce emissions in the industry, transportation, and building sectors, which will further increase the demand for zero-carbon electricity supply. In 2022, more than 60% of the global electricity supply was still from fossil fuels. Therefore, the construction of a zero-carbon power system has become a common issue faced by all countries.

The zero-carbon power system will face dual uncertainties from the supply and demand sides; this will require more system flexibility resources to meet the power balance and to realize a larger scale of renewable energy integration. On the supply side, renewable energy generation technologies like wind power, solar photovoltaic, and hydropower are characterized by intermittency. On the demand side, power loads have become more volatile with the influence of multiple factors such as electrification and frequent extreme weather events. During the low-carbon transition, the reliance on fossil fuel power capacity like coal and gas, which conventionally served as major flexibility resources, will continue to decline. Power systems will need more carbon-free flexibility resources to cope with supply-demand uncertainties and achieve the power balance on multiple time frames: from the annual level down to management of seconds.

In 2021, the State Council of China issued the *Action Plan for Carbon Dioxide Peaking Before 2030*. The Action Plan noted two necessities: (1) to accelerate the construction of the New Power System with an increasing share in renewable energy sources; and (2) to develop flexibility resources from generation, grid, load, and storage to promote the realization of carbon peaking and carbon neutrality. The Action Plan clarified that building a robust and smart power grid will require "significantly improving the power system flexibility capability" and "accelerating the construction of flexible power generation sources." It also specifies that "guiding captive power plants, traditional intensive industrial load, industrial and commercial interruptible load, electric vehicle charging network as well as virtual power plants providing system flexibility" are key to this transition.

Along with economic development and electrification of other sectors, China's electricity demand will continue to grow, and the value of demand-side flexibility (DSF) will become increasingly significant. RMI's 2023 report *Exploring China's Pathway to a New Power System: Bringing Modern Elements Online Before Phasing Out the Old* proposed that the flexible participation of the demand side in power balancing is one of the main characteristics of the New Power System. It argued that promoting an observable and controllable demand side is an effective means of improving system flexibility.

In recent years, the national power supply and demand balance has been tight, and strengthening load management and developing DSF resources have become urgent tasks in building a new power system. At the national level, the compound annual growth rate of electricity consumption between 2015 and 2022 reached 6.1%. The growth rate of the peak load was even higher at 7.1%, showing greater volatility on the load side. At the provincial level, the tight power balance has been more serious in some areas: in July and August 2022, power grids in 21 provinces had record high electricity consumption loads, and eastern and central China had very tight power balance. In addition to the traditional summer load peak, with the adjustment and upgrading of the consumption and industrial structure, the load curves in eastern, central, and southern China have hit peaks in winter as well. In February 2022, the tight power balance occurred in certain periods in Jiangxi, Hunan, Sichuan, Chongqing, Shanghai, and Guizhou. There is an urgent need to optimize and upgrade the demand-side management to help close the gap between supply and demand.

Currently, China's demand-side management is still dominated by orderly electricity consumption (regulated measures) and has not yet formed a mature market-based operation mechanism. There are insufficient load management technology reserves and a lack of user awareness in demand response. In 2023, the National Development and Reform Commission revised the *Measures on Demand-side Management of Electricity (2023 edition)* . It added a specific chapter on demand response for the first time, emphasizing the promotion of demand response toward marketization, normalization, aggregation, and reliability. The target demand response capacity of each province will consist of 3% to 5% of the annual peak load by 2025. It also clarified the prioritization of market-based demand response over regulated measures and required the reasonable implementation of orderly electricity consumption.

Whether for reasonable orderly electricity consumption or market-based demand response, mapping out the technical feasibility of user-side demand response and establishing a flexibility resource base form the necessary groundwork. The electricity consumption of industrial users in China has reached 5,700 terawatt-hours (TWh), accounting for 65% of total electricity consumption in 2022. Considering the comprehensive industrial system and diversified load structure, the industrial sector theoretically possesses significant potential for developing DSF. Due to the large single-user power consumption and low communication cost, industrial users are the prioritized load resources in the current practice of orderly electricity consumption. An in-depth investigation of the demand response capabilities of different industries and enterprises can help to formulate a more reasonable scheme for power demand-side management.

Based on this background, RMI China's DSF research first focuses on the industrial sector. This research will dive deep into the technical issues of developing industrial DSF, that is, the potential of demand response in various industrial production processes. Combining domestic and international practice and progress, this report will identify the main sources and potentials of industrial DSF; explore the technical, economic, and managerial challenges; and specify the important role the industrial DSF plays in building the new power system.

Definition and Development of Industrial DSF

Importance of DSF in the future power system

Power system flexibility refers to the ability of a power system to respond quickly to large power and energy fluctuations on both the supply and demand side under certain economic constraints. Under the goal of achieving carbon peaking before 2030 and carbon neutrality by 2060, China's installed capacity of renewable energy has notably increased, and the share of renewable power generation has grown rapidly. In October 2021, the State Council issued the *Action Plan for Carbon Dioxide Peaking Before 2030*[1] and stated the goal of building the new power system with a gradual increase of renewable energy share.

In the Action Plan, the proportion of non-fossil energy consumption is expected to reach about 20% by 2025 and 25% by 2030. By the end of 2022, China's wind and solar photovoltaic (PV) power accounted for 29.6% of total installed capacity in the power system and 13.7% of total power generation. In June 2023, the National Energy Administration (NEA) released the *Blue Book on the Development of New Power Systems*,[2] maintaining that it is necessary to promote renewable energy as the main source of incremental power generation in the accelerated transition period of building the new power system by 2030. It also stated that the installed capacity mix and power generation mix of renewable energy should be over 40% and 20%, respectively, by 2030.

This proposed change is expected to lead to non-fossil power sources gradually becoming the main component of installed capacity and power generation during the overall formation period (2030–45) and consolidation and improvement period (2045–60). As the building of the new power system progresses, the penetration rate of renewable energy power represented by wind and solar PV will continue to increase rapidly, exacerbating the volatility and uncertainty of the power supply. Coupled with the volatility of the demand side, the power system will face a more severe challenge of balancing supply and demand in the future.[3] Therefore, the flexibility of the power system urgently needs to be improved to ensure the reliability, stability, and security of grid operation.

It is difficult to rely on a single technology or a single path to realize the enhancement of power system flexibility, and it is necessary to explore the potential across the whole value chain of the power system. At present, power system flexibility in China mainly comes from retrofitted flexible coal power (with a lower minimal stable level), conventional hydropower, pumped storage, electrochemical energy storage, and gas power units. Among them, the flexibility retrofitting rate of coal power units is still at a low level.

In the 13th Five-Year Plan period, the flexibility retrofitting of coal power was completed in less than 60 gigawatts (GW) out of 1,140 GW total coal fleet, and the problems of slow ramping rate, long start and shutdown time, and high coal consumption also prevent coal power units from becoming ideal flexibility providers. Conventional hydropower has geographic and seasonal limitations, and its actual flexibility capacity is also affected by joint dispatch of cascade hydropower plants and agricultural irrigation. Additionally, gas power is subject to the energy security constraints of insufficient domestic gas supply. Pumped storage also has geographical limitations with a long construction cycle. Electrochemical energy storage faces problems such as shorter durations and higher costs.

By the end of 2022, power resources with fast ramping rates such as pumped storage, electrochemical storage, and gas-fired power generation accounted for only 6.6% of the total installed capacity of the power system. Therefore, the stability and reliability needs of the power system cannot be met by generation-side flexibility alone. Grid-side flexibility is also affected by numerous complicating factors, such as line transmission capacity, regional coordination, and power market maturity. DSF, however, is widely distributed, can quickly respond to changes in power supply and demand, and realizes multi-timescale demand response with lower cost. Therefore, the development of DSF has become an urgent need to ensure the secure and stable operation of the power grid.

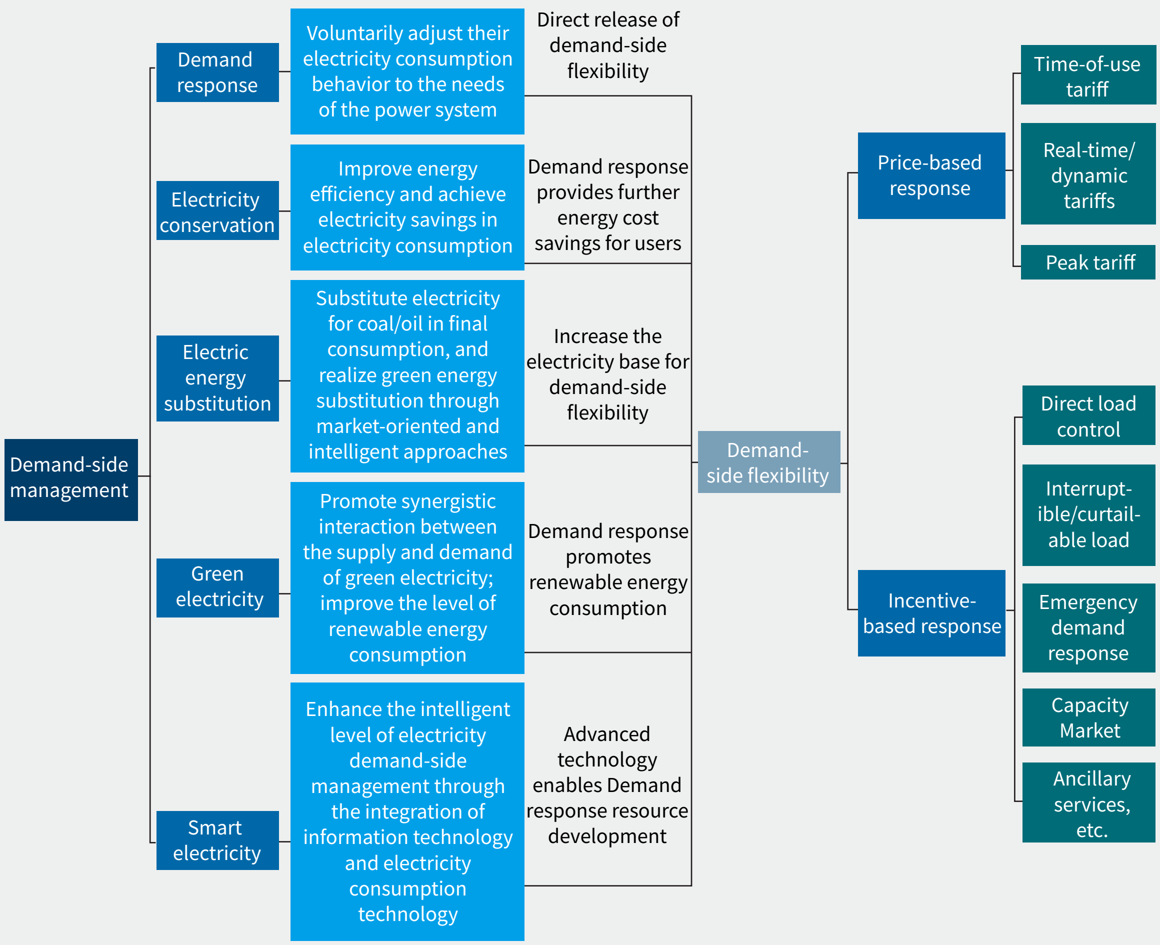
Definition of DSF and relevant concepts

DSF usually refers to the ability of electricity users to adjust their own consumption behavior according to the needs of the power system operation, and it is an important component of electric power demand-side management.

The third edition of *Measures on Demand-Side Management of Electricity*, published in September 2023,[4] states that demand-side management consists of three parts. The first is strengthening the management of electricity consumption of the whole society. The second involves adopting reasonably and feasibly technical, economic, and management measures to optimize the allocation of power resources. And the third is implementing demand response, electricity conservation, electric energy substitution, green electricity consumption, intelligent electricity consumption, and orderly electricity consumption, so as to promote secure operation and carbon reduction of the power system, improve efficiency, and reduce energy intensity. Green electricity consumption requires DSF to promote renewable energy consumption and achieve green transformation, while intelligent electricity consumption helps electricity users explore DSF through the integration of information and communication technology and power consumption technology.

The potential of DSF is mainly applied through demand response. Demand response refers to the voluntary adjustment of electricity consumption behavior by users based on the needs of power system operation. Demand response can achieve peak shaving and valley filling, which improves the flexibility of the power system, ensures the security and stability of power system operation, and promotes the consumption of renewable energy power.[5] Different from orderly electricity consumption, demand response involves an active participation in the adjustment of electricity consumption behavior and is an important measure of demand-side management. The relation and distinction among demand-side management, DSF, and demand response are shown in Exhibit 1.

Exhibit 1 **Definition and classification of demand-side management and demand response**



RMI Graphic. Source: National Development and Reform Commission (NDRC), RMI

History and status quo of demand-side management in China

Since the first edition of the *Measures on Demand-Side Management of Electricity* in 2011,[6] China has made efforts to promote demand response, energy conservation and intensity reduction, green power consumption, electricity security, and other demand-side management practices (see Exhibit 2).

- In 2015, the Central Committee of the Communist Party of China (CPC) and the State Council issued *Several Opinions on Deepening the Reform of the Power System.*[7] This document suggested that power companies actively carry out demand-side management and promote demand response.

- In 2016, the *National Strategy for the Revolution in Energy Production and Consumption (2016–2030)* explicitly proposed implementing special actions for demand-side management of electricity in the industrial sector.[8] In the same year, the Ministry of Industry and Information Technology issued *The Special Action Plan for Demand-Side Management of Electricity in the*

Industrial Sector (2016–2020).[9] It proposed building a platform for demand-side management of electricity and organizing demonstrations and promotions in key industries such as iron and steel, nonferrous metals, and chemicals. It suggested accomplishing this through the development of working guidelines and other key tasks to comprehensively improve the efficiency of energy consumption and demand response capacity in the industrial sector.

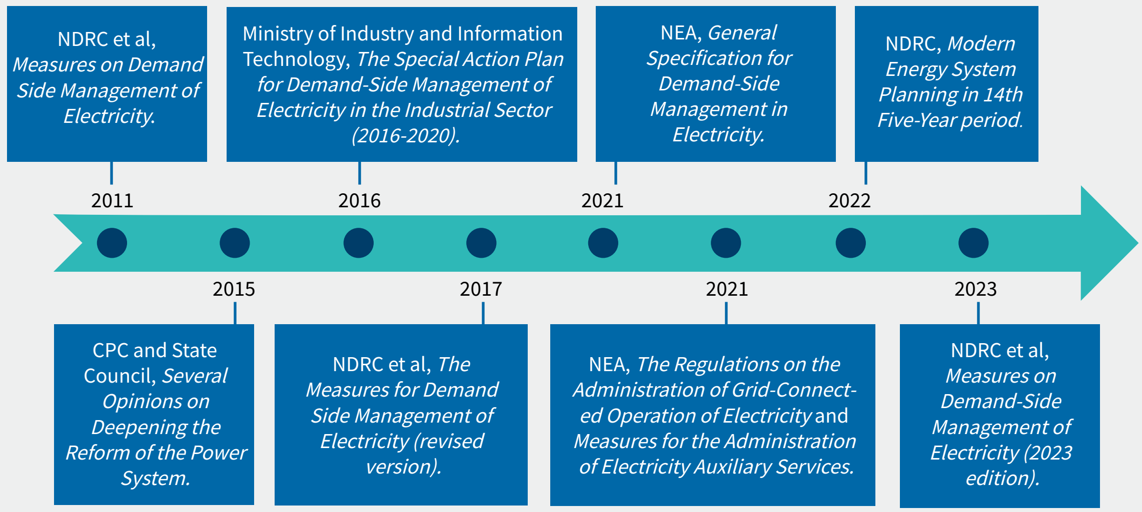
- In 2017, the NDRC along with six other ministries issued *The Measures for Demand-Side Management of Electricity (revised version)*,[10] which emphasized the necessity of summarizing and promoting the pilot experience of demand response. The publication also proposed an economic incentive mechanism to establish the coordination and interaction between demand response and renewable energy power consumption.

- In 2021, the Center for the Promotion of Demand-Side Management of Electricity in the Industrial Sector took the lead in organizing the compilation of two standards. These were the *General Specification for Demand-Side Management in Electricity Part 1: General Provisions* and the *General Specification for Demand-Side Management in Electricity Part 2: Terminology*.[11] These standards were put forward by the National Technical Committee on Standardization of Electricity Demand-Side Management. In the same year, the NEA revised and issued *The Regulations on the Administration of Grid-Connected Operation of Electricity*[12] and the *Measures for the Administration of Electricity Ancillary Services*.[13] These publications suggested expanding new participants of electricity ancillary services, enriching new varieties of electricity ancillary services, and designing new mechanisms for user cost allocation and market-based pricing formation.

- In January 2022, the NDRC issued the *Modern Energy System Planning in 14th Five-Year Period* and established the importance of industrial resources as flexibility providers.[14] The document asked producers of large industrial loads to participate in the ancillary service market and encouraged producers of electrolytic aluminum, ferroalloys, polysilicon, and other electricity-price-sensitive, energy-intensive loads to advance their production procedures and provide flexibility in the form of interruptible and controllable loads.

  In September 2023, NDRC and other ministries reissued the *Measures on Demand-side Management of Electricity (2023 edition)*.[15] This publication clearly asserted that by 2025 the target demand response capacity of each province will reach 3% to 5% of the peak load, and the provinces with an annual peak-valley load ratio exceeding 40% will reach 5% or more. The publication stated that by 2030, the large-scale, real-time demand response capacity can be established and the sharing and integration of flexibility resources within the grid area can be realized, and that these solutions can be combined with the ancillary services market and electric energy market transactions.

Exhibit 2 **Demand-side management–related policy roadmap**



RMI Graphic. Source: RMI analysis

Industry as potential source of DSF

Industrial loads, with a large load base and high demand response potential, are an important source of DSF in the power system. Demand-side users of electricity mainly include industrial, commercial, and residential sectors.[16] The scope of participation in demand response is more extensive and includes new demand-side resources such as microgrids, distributed smart grids, virtual power plants, electric vehicle charging facilities, and user-side generation-grid–load-storage integration.[17]

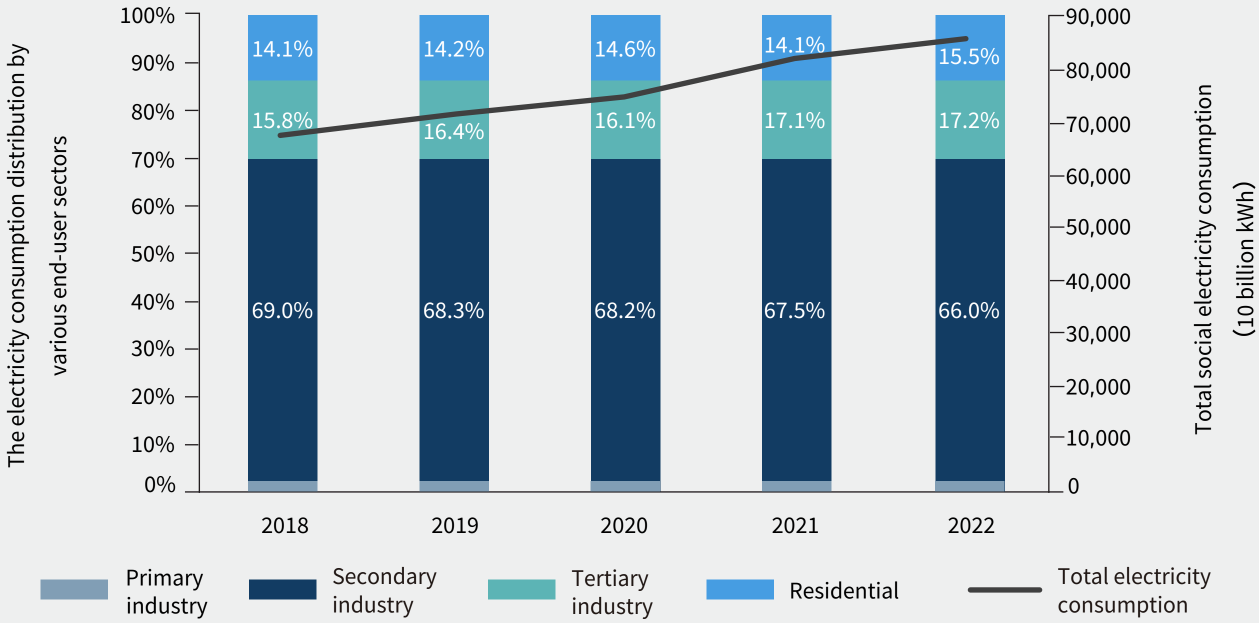
As the main driving force of economic development in China, the industrial sector makes up the highest proportion of electricity consumption among all users (see Exhibit 3). According to the China Statistical Yearbook 2022,[18] the added value from all industries in China exceeded 40 trillion renminbi, accounting for 33.2% of GDP. Electricity consumption by industries reached 5,700 TWh, accounting for 66% of total electricity consumption. This far exceeds that of commercial and residential users.

Along with the continuous development of the industrial economy and decarbonization of certain industries through electrification, the electricity consumption of the industrial sector will continue to increase. In addition, China's industrial load structure is rich with high flexibility potential and high operability. According to the China Electric Power Research Institute (CEPRI), the research arm of State Grid, the top 15 contributors in terms of peak shaving and valley filling potential are all from the industrial sector, including cement, iron and steel, ferroalloys, silicon carbide, aluminum electrolysis, and magnesium electrolysis. Electricity price–sensitive industries like cement, electrolysis, and iron and steel will have significant benefits from participation in demand response.

In terms of organization and management, the communication cost for industrial users is relatively lower, and a limited number of high-quality industrial demand response resources can be spotted through resource census and flexibility assessment. And typical grid operation situations, such as peak shaving, valley filling, and renewable energy consumption, can be achieved by carrying out targeted and regular industrial demand response business.

Exhibit 3

Share of electricity consumption of various types of electricity users in China



RMI Graphic. Source: China Statistical Yearbook 2022, RMI

The development of industrial DSF is of great significance to guarantee the stability and reliability of China's power system. Although China introduced demand-side management back in the 1990s, it mainly relied on the regulated and planned dispatch mode.

At present, the priority rules of orderly electricity consumption are vague, and the power supply of industrial enterprises is often forced to cut off, causing plant shutdowns and economic losses. This shows the insufficiency of active demand response of industrial load in the power system. In the effort to achieve carbon neutrality and establish the new power system, one primary focus of power system construction has been to achieve the observability and controllability of the demand side and flexible participation in the power balancing. Currently, several provinces have pilot programs to promote demand response and virtual power plants.

The development of information technology and power market reform have provided important technical support and a supportive market environment for a new round of developing industrial DSF.

- From a technical perspective, with the implementation of the energy digitization strategy, industrial enterprises have gradually formed the unique advantage of sensing-communication-computing-control integration. This empowers industrial lean production and indirectly empowers energy saving, carbon reduction, and participation in power grid interaction. For example, the iron and steel industry has proposed the goal of advanced automation, extreme flexibility, and extreme energy efficiency. With the promotion and integration of industrial internet and energy internet, the model and data-driven approach will fully consider the coupling of electric and nonelectric parameters in the production and operation process. Through the quantification of the production, security, and economic constraints, it can achieve the decoupling of flexible loads in the actual production and master the precise temporal and spatial characteristics of load resources from temperature control, electrolysis, ball milling, and energy storage.

- From a market perspective, with the progress of power market reform, demand-side resources have also been given a more important role in market participation. According to the *Measures on Demand-side Management of Electricity (2023 edition)*, power grid enterprises should accelerate the construction of an available and controllable demand response resource base. All types of demand response resources meeting the requirements of the electricity market access are eligible to participate in the market transactions of electric energy and ancillary services.

  The document also suggested that demand response entities be included in the scope of the capacity mechanism to establish and improve the demand response pricing mechanism in accordance with the electricity market. This means that industrial enterprises can not only reduce electricity costs through peak shaving, valley filling, and optimizing electricity consumption in the electric energy market, but also maintain the stable operation of the power system. This can be achieved through direct or indirect participation (e.g., load aggregators, power retail companies, virtual power plant operators, integrated energy service providers, and other demand-side management service entities) in the ancillary service market, capacity mechanism, and demand response mechanism.

  Existing demand response incentives are mainly from financial special funds, interprovincial renewable energy trading spread surplus, seasonal peak tariffs, renewable energy consumption subsidies, spot market balancing funds, and ancillary service fees. Incentives are expected to be incorporated into the system operation costs of transmission and distribution tariffs in the future. Power market reform provides more economic incentives for industrial enterprises to develop and use DSF, and it mobilizes the initiatives of enterprises to participate in demand-side management.

Purpose of the report

Based on this background, the RMI China DSF research will initially focus on the industrial sector. This research will discuss the technical feasibility and potential of developing DSF during different industrial production processes. Only when the flexible load characteristics of each process are clarified can the flexibility potential be fully realized through the design of market mechanisms. Therefore, this report will summarize the development status; identify the main flexibility sources and potentials; and explore the technical, economic, and managerial challenges of industrial DSF development based on literature review and global practice, combined with expert interviews and site visits. The report aims to help industrial DSF play an important role in ensuring reliability and stability of the power system, as well as accelerating the decarbonization process.

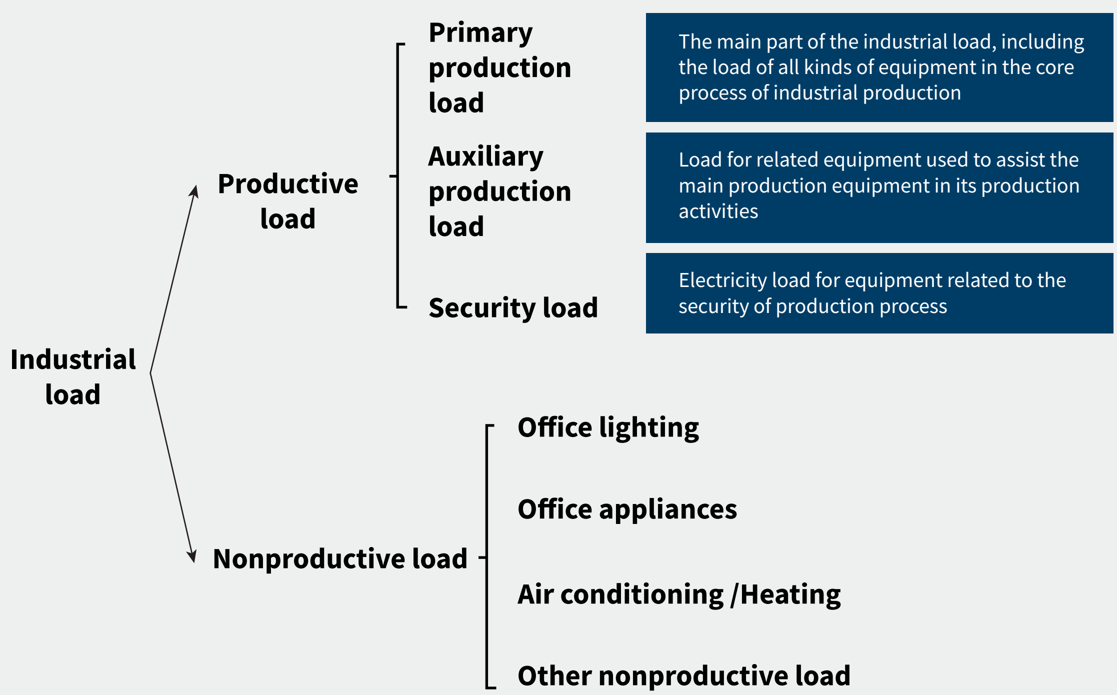
Main Sources and Potential of Industrial DSF

Classification of industrial loads

It is necessary to initially understand the characteristics of various types of loads in the industrial production process to further explore the load flexibility potential and make reasonable decisions about demand response.

From the perspective of function, industrial load can be divided into productive loads and nonproductive loads (see Exhibit 4). Productive load refers to the electricity consumed in the industrial production process for driving equipment, electric heating, or electrochemical processes.[19] Productive load can be further divided into three categories: primary production load, auxiliary production load, and security load. The flexibility potential of productive loads depends on factors such as the electric load, the operation frequency, and the reserved load of equipment. Nonproductive load refers to electricity used for office lighting, office appliances, air conditioning, heating, etc. The electricity consumption of equipment and its load share can be quite different due to production process variations in different industries.[20] In most cases, the productive load is the main source of flexibility in industry.

Exhibit 4 **Classification of industrial load by function**

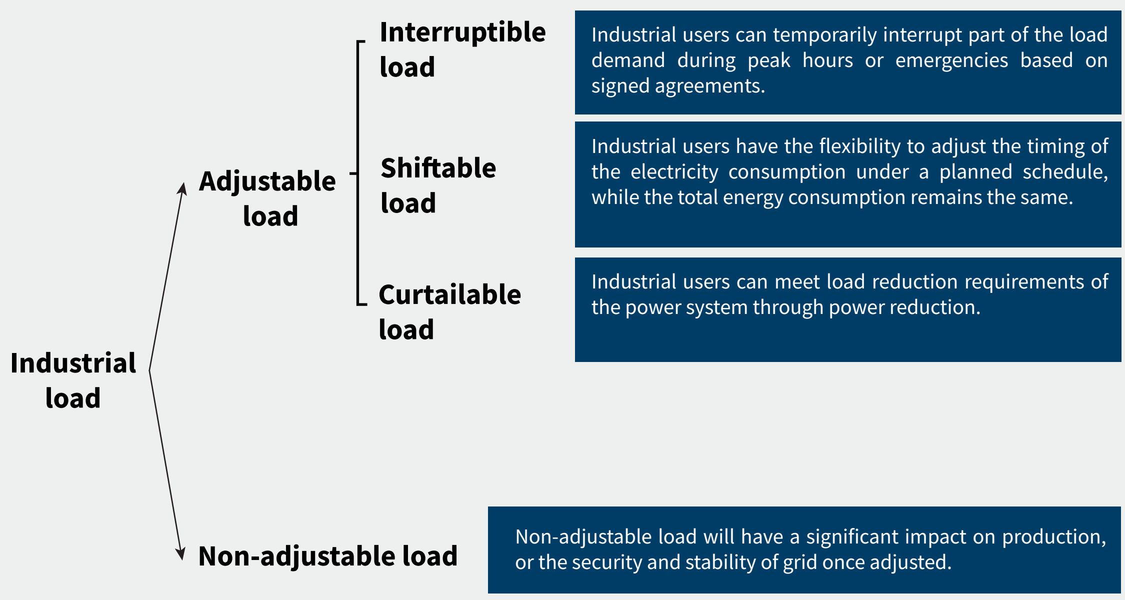


RMI Graphic. Source: CEPRI, RMI

From the perspective of demand response strategies, industrial load can be classified into two categories: adjustable and non-adjustable loads. Nonflexible loads usually have high requirements for the reliability of power supply. Once the electricity consumption behavior is changed, it will have a significant impact on the production of users or the security of the power grid. Therefore, it is harder to alter nonflexible load.

Flexible load includes interruptible load, shiftable load, and curtailable load (see Exhibit 5). Interruptible load means that industrial users can temporarily interrupt part of the load during peak hours or emergencies based on signed agreements. This type of load can typically provide minute-level flexibility and allow for a quick response to power system needs. Shiftable load means that industrial users have the flexibility to adjust the timing of electricity consumption under a planned schedule, while the total energy consumption remains the same. Curtailable load refers to loads that can be used by industrial users to meet load shaving requirements of the power system. Both load shifting and load shaving require frequent switchgear controls and are usually applicable to hourly and intraday time scales.

Exhibit 5 **Classification of industrial load by regulation ability**



RMI Graphic. Source: CEPRI, RMI

Approaches for demand response in different industries

Based on the production process characteristics, industries can be classified into continuous production industries and discontinuous production industries, which correspond to differentiated demand response strategies respectively.[21]

Continuous production industry, also known as process industry, refers to the process in which the materials flow uniformly and continuously according to a certain process sequence, change shape and performance in the flow, and finally form the product. Typical continuous production industry includes chemical, iron and steel, and aluminum production. Due to the continuity of the production process, those industries usually require a relatively stable load supply and a high level of security and reliability requirements. These industries are generally suitable for providing DSF through load shifting and load shedding.

Discontinuous production industry, also known as discrete industry, refers to the production of individual products that can be counted by specific units instead of by weight or volume. This type of industry is characterized by breaking down the process of producing a single product into multiple units and assembling the final product at the end. These industries usually have high load flexibility, and thus the choice of demand response is more diverse. Typical discontinuous production industries include food, machinery, and equipment manufacturing.

Demand response can be realized by adjusting operating conditions such as production temperature, production speed, input current, or input voltage. A typical industry that adjusts load by temperature control is the iron and steel industry. In the steelmaking process, the load is adjusted by controlling the feedstock feeding time, the high-temperature refining time, and the speed of raising or lowering temperature of the steel refining furnace. A typical industrial demand response by adjusting the current and voltage is aluminum electrolysis. Enterprises can change the real-time power consumption through an automatic control system and without interrupting the melting furnace. When there is insufficient or excessive electricity supply, melting furnaces in the electrolysis tanks will reduce or increase the input voltage, respectively, or they can generate large load variation in a short time through the start and shutdown of different electrolysis tanks to provide flexibility.

In addition to the DSF from production processes, some industries can also participate in demand response through distributed generation resources. Industrial users can reduce the demand from the grid by increasing power supply from captive power plants or backup batteries to provide system flexibility. For example, according to Global Energy Monitor, the installed capacity of operating captive coal power plants totals more than 130 gigawatts (GW) in China, accounting for 12% of all installed capacity. Those plants are mainly concentrated in the industries that produce aluminum (~76 GW), chemicals (~26 GW), and iron and steel (~10 GW). Captive power plants can be important sources capable of providing industrial DSF and thus should not be overlooked.

During the industrial green transition process, the need to decarbonize the enterprise's captive power plants is also urgent. In addition to retrofitting traditional coal power units for higher efficiency and lower emissions, investment in renewable energy and energy storage may be a long-term strategy. This will help enterprises to avoid the risk of price fluctuations in fossil fuels and to provide more zero-carbon flexibility sources for the power grid.

Summary of key industries' DSF

The major flexibility devices, temporal characteristics, and potential of participation in demand response vary significantly among different industries.[22] Exhibit 6 illustrates relevant survey results in some typical industries. Under ideal conditions of policy, technology, and market policy, the textile industry can achieve a maximum demand response level of around 35%. The share of flexible load is about 22% for the aluminum industry and about 20% for the iron and steel industry. The demand response potential of the cement, glass, and equipment manufacturing industries is also above 20%.[23]

Exhibit 6 Major flexibility sources, demand response temporal parameters, and potential for key industries

Industry segments	Major flexibility sources/devices	Demand response temporal parameters			Demand response potential (of total load)
		Lead time	Response duration	Recovery time *	
Electrolytic aluminum 	Aluminum reduction cell, captive power plant	2h (aluminum reduction cell)	1—2h	2h (aluminum reduction cell)	20%
Iron and steel (steelmaking) 	Electric arc furnace, rolling line, captive power plant	Per shift (steel rolling) 10—30min (electric arc furnace)	0.5—1h	Per shift (steel rolling) 10—30min (electric arc furnace)	20%
Ferroalloy 	Submerged arc furnace, electric arc furnace, reduction furnace	1—2h	0.5—4h	1—2h	30%
Cement 	Rotary kiln, vertical kiln	1—2h	0.5—2h	1—2h	24%
Textile 	Loom, texturing machine	0.5—1h	0.5—4h	0.5—1h	35%
Glass 	Air compressor, annealing kiln, glass melting kiln, cold end glass cutting machine	0.5—2h	0.5—3h	0.5—2h	25%
Equipment manufacturing 	Melting furnace, heat treatment furnace, high frequency furnace	1—2h	0.5—3h	1—2h	20%

(Timeline scale in each temporal parameter cell: s, min, 1h, 2h, 4h, 8h)

* Recovery time is defined as the return to normal operation from a certain demand response state, not from an interrupted state of operation (h = hours).

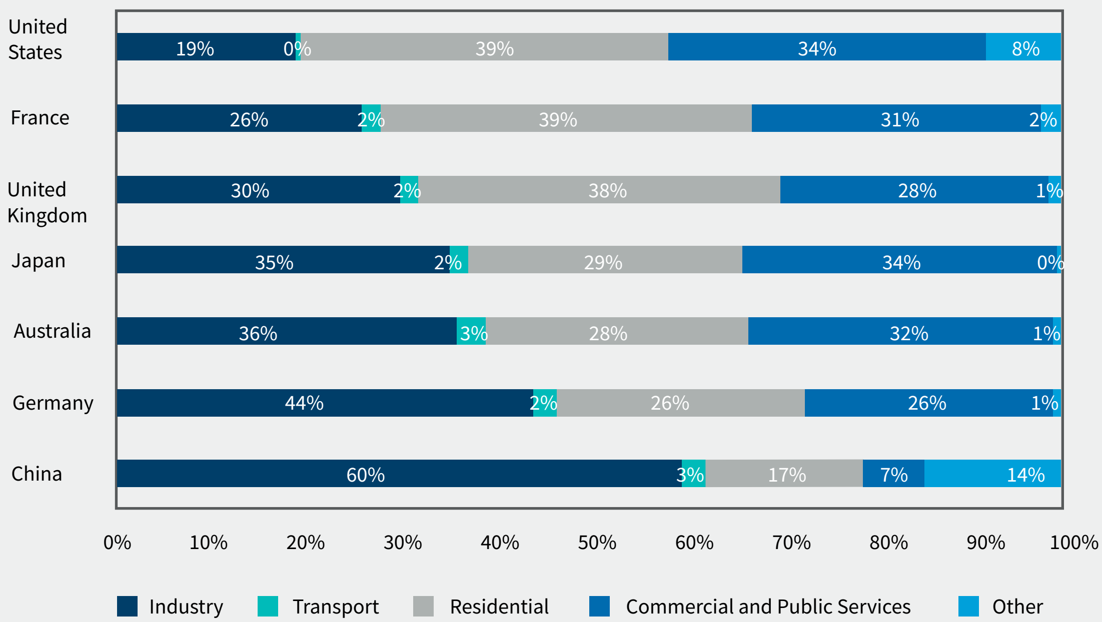
RMI Graphic. Source: State Grid Electric Power Research Institute, CEPRI, RMI

Global and Domestic Practice in Industrial DSF

Global practice in industrial DSF

The potential for industrial DSF is of great importance in all countries around the world. Exhibit 7 shows the structure of final electricity consumption in several countries. Compared with China, which has the highest share of industrial electricity consumption (60%), Germany's industrial electricity consumption share is 44%. To achieve the goal of 80% power generation from renewables by 2030, Germany has been devoted to exploring DSF resources. Statistics show that industrial demand response potential in Germany is up to 10 GW, accounting for about 13% of the peak load of the country.[24] According to the US Environmental Protection Agency, the United States achieved peak shaving of 12 GW through demand response mechanisms in 2021, of which industrial users contributed 45.6%, although the proportion of industrial electricity consumption is only 19.0%. These cases show the superiority of exploring DSF for industrial users.

Exhibit 7 **Structure of electricity consumption by sector in seven countries in 2020**

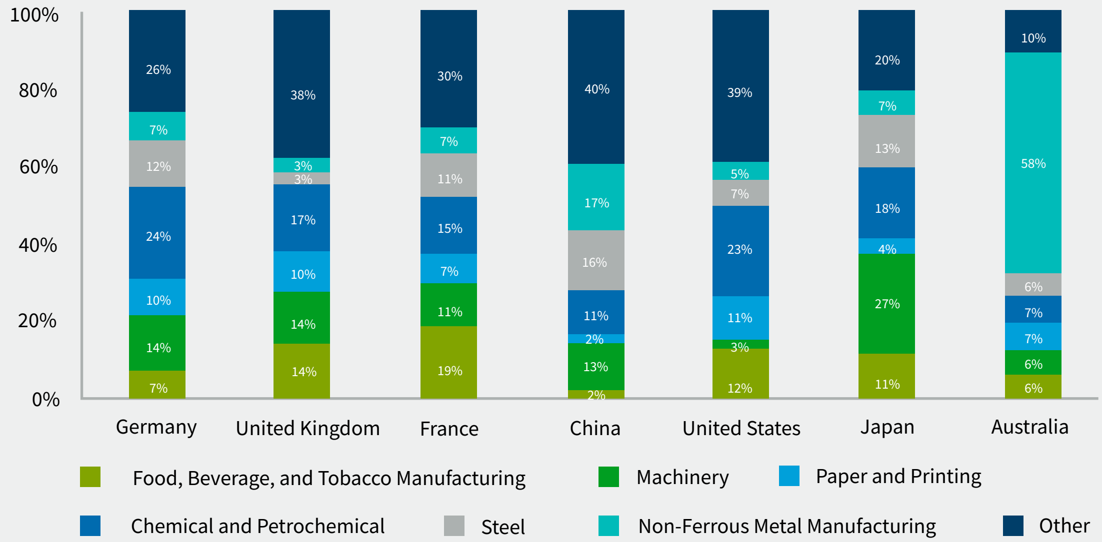


RMI Graphic. Source: International Energy Agency, RMI

Due to differences in industrial structure and technology levels, the key industries and corresponding DSF potential vary among countries. Exhibit 8 shows the share of key industries in electricity final consumption. China, Germany, and Japan have higher shares of electricity consumption in iron and steel, which shows the urgent need to develop DSF in the iron and steel industry for these countries.

For Australia, nonferrous metal manufacturing constitutes a higher share of electricity consumption, and the DSF potential of this industry may be more significant. Note that food manufacturing consumes a notable share in developed countries such as France, the UK, and the United States.

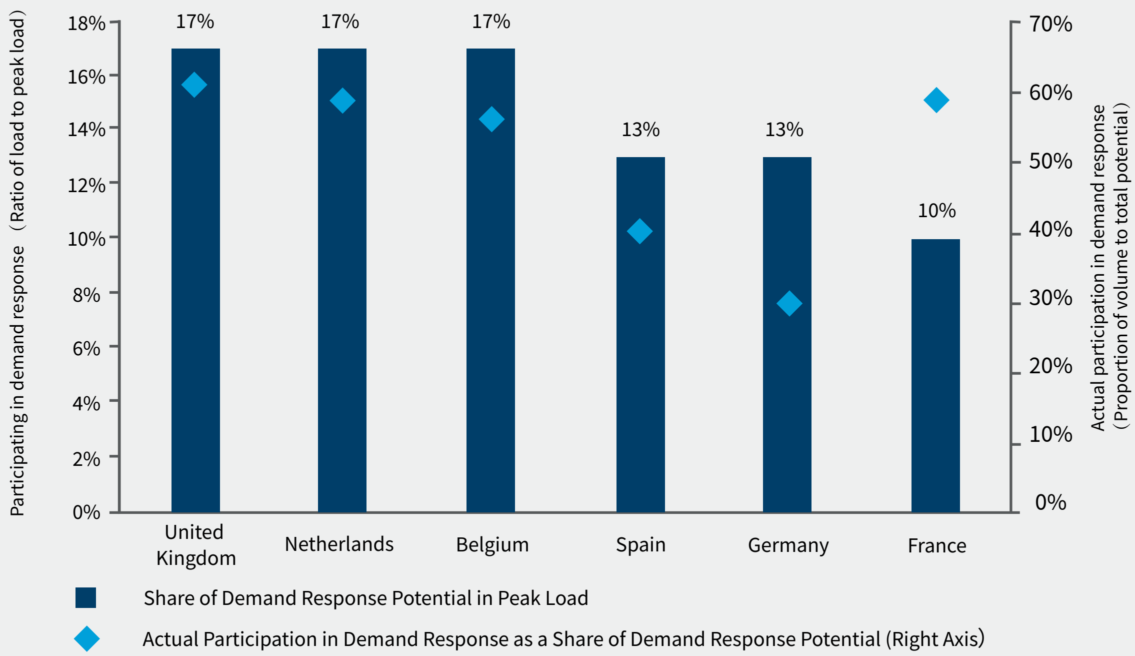
Exhibit 8 **Electricity consumption share of key industries in seven countries**



RMI Graphic. Source: *China Statistical Yearbook 2022*, TenneT; US Energy Information Administratio; Japan Electricity Utilities Alliance; Australian Department of Climate Change, Energy, Environment and Water; RMI

Some developed countries in Europe have made significant progress in exploring and applying industrial DSF. Exhibit 9 shows the theoretical demand response potential and actual demand response level of industries in six European countries, respectively. Among them, the UK, the Netherlands, and Belgium have the highest proportion of industrial demand response potential, accounting for 17% of peak load, while that of other countries also exceeds 10%. In terms of implementation, the actual participation level of demand response in the UK, France, and the Netherlands has been about 60% of the theoretical potential, while that in Germany and Spain is relatively lower, about 30%.[25]

Exhibit 9 **Theoretical potential and actual participation level of demand response in six countries in 2020**



RMI Graphic. Source: European Network of Transmission System Operators, TenneT, RMI

Domestic practice in industrial DSF

Development of industrial DSF in China is still at the embryonic stage, but recent trends have shown advances in industrial production and information technologies. Improvements in demand response–related mechanisms and supporting policies have paved the path for large-scale development of industrial DSF.[26]

- At the technical level, the upgrading of certain industrial equipment and production processes in recent years has contributed to the practice of DSF. For example, aluminum electrolysis enterprises can upgrade diode rectifiers to thyristor rectifiers with a wider range of demand response levels. In the iron and steel industry, the blast furnace–basic oxygen furnace (BF-BOF) is being replaced by electric arc furnace secondary steelmaking, which brings a higher load and electricity consumption. The development of information technology such as big data, cloud computing, and industrial internet has enabled industries to implement load control more accurately and interact with the power grid in real time.

- At the level of market and environmental policy, several provinces have introduced targeted demand response policies and carried out corresponding practices. Exhibit 10 summarizes the demand response participant types, target, programs, and pricing mechanisms of existing provincial demand response policies. Industries and major electricity users are included as major participants in demand response in all provinces, prompting industries to explore the potential of DSF through economic incentives. From the perspective of pricing mechanisms, each province has set different price ranges or compensation levels for various demand response programs to fully incentivize various types of users to participate in demand response.

Exhibit 10 **Summary of existing demand response (DR) policies at provincial level in China**

Provinces	Policy documents	Participant types	Demand response target	Demand response programs	Pricing mechanism
Yunnan	*Electricity Demand Response Program of Yunnan Province in 2023*, 2023.4	DR level ≥ 1MW: Industrial load, commercial interruptible load, building load, demand-side energy storage, electric vehicle charging facilities, distributed power generation, etc.	—	Market-based/invitation-based/ real-time-based offer; peak shaving; valley filling	(1) Real-time = 2.5 renminbi/kWh (2) Invitation-based: (a)Peak shaving = 0–5 renminbi/kWh Valley filling = 0–1 renminbi/kWh
Gansu	*Gansu Electricity Demand Response Market Implementation Program (Trial)*, 2023.4	DR level ≥ 1 MW and duration ≥ 1 h for electricity consumers, load aggregators, etc.	No less than 1 GW	Day-ahead/intraday demand response	Market clearing price through centralized bidding
Sichuan	*Implementation Plan for Market-based Demand-Side Response of Electricity in Sichuan Province for th Year 2023*, 2023.4	DR level ≥ 1 MW and duration ≥ 1 h for commercial and industrial users of 10 kilovolts (kV) and above, load aggregators, etc.	5% of peak load	Day-ahead demand response	Market clearing price through centralized bidding
Hebei	*Notice of the Development and Reform Commission of Hebei Province on Further Improving the Operation of the Electricity Demand Response Market in the Southern Power Grid of Hebei Province*, 2023.4	Electricity users of 10 kV and above; DR level ≥ 5 MW and duration ≥ 2 h for load aggregators	—	Day-ahead/intraday/real-time demand response	When DR rate: (1) < 80% there is no subsidy; (2) 80%–120% = effective response power * clearing price; (3) 120%–150% = effective response power * 0.5 * clearing price; (4) > 150% there is no subsidy
Guizhou	*Implementation Program for Electricity Demand Response in Guizhou Province (Trial)*, 2023.4	DR level ≥ 1 MW and duration ≥ 1 h for electricity users, load aggregators, etc.	5% of peak load	Peak shaving; valley filling; invitation-based and real-time-based	Up to 1.5 renminbi/kWh
Tianjin	*Implementing Rules for Electricity Demand Response during Spring Festival in Tianjin 2023*, 2023.1	DR level ≥ 6 megawatt-hours (MWh) for load aggregators, VPP; DR level ≥ 3 MWh for industrial users; DR level ≥ 0.6 MWh for nonindustrial users	—	Invitation-based valley filling	Invitation-based valley filling = 1 renminbi/kWh
Jiangsu	*Implementing Rules for Electricity Demand Response in Jiangsu Province (Revised Exposure Draft)*, 2022.10	DR level ≥ 1 MW for commercial and industrial load, residential load, load aggregators, etc.	5% or more of peak load	Interruptible load; valley filling for renewable energy consumption; contracted/real-time response	(1) Interruptible load is 10 renminbi/kW for ≤ 2 h; 12 renminbi/kW for > 2 h to ≤ 4 h, 15 renminbi/kW for > 4 h (2) Valley filling = 5 renminbi/kW for valley period and 8 renminbi/kW for flat period
Ningxia	*Measures for the Management of Electricity Demand Response in the Ningxia Hui Autonomous Region*, 2022.6	DR level ≥ 1 MW and duration ≥ 1 h for electricity users, load aggregators, etc.	No more than 5% of peak load	Peak shaving; valley filling	(1) Peak shaving = 2 renminbi/kWh (2) Valley filling = 0.35 renminbi/kWh
Shandong	*Provincial Electricity Interruptible Load Demand Response Work Program for 2022*, 2022.6	DR level ≥ 1 MW for industrial users and load aggregators; DR level ≥ 0.4 MW for nonindustrial users and load aggregators; DR level ≥ 5 MW and duration ≥ 2 h, lead time ≤ 4 h for VPP, energy storage operators	Potential peak shaving is 6 GW; potential valley filling is more than 2 GW; actual peak shaving is 2 GW; actual valley filling is more than 1 GW	Emergency/economy interruptible load	(1) Emergency interruptible load has capacity compensation no more than 2–4 renminbi/kW/month based on lead time, energy (kWh) compensation based on DR volume, and spot price (2) Economy interruptible load is based on DR volume and spot price

Provinces	Policy documents	Participant types	Demand response target	Demand response programs	Pricing mechanism
Fujian	*Implementation Program for Electricity Demand Response in Fujian Province (for Trial Implementation)*, 2022.5	Electricity users of 10 kV and above, load aggregators with DR level ≥ 2.5 MW for energy storage resource users, etc.	5% of the peak load	Day-ahead/intraday demand response	Market clearing price through centralized bidding
Chongqing	*Demand Response Implementation Program for Chongqing Power Grid in 2022 (Trial)*, 2022.4	DR level ≥ 1 MW for industrial users; DR level ≥ 0.1 MW for nonindustrial users; DR level ≥ 5 MW for load aggregators	—	Invitation-based peak shaving and valley filling	(1) Peak shaving: industrial = 10 renminbi/kW others = 15 renminbi/kW (2) Valley filling = 1 renminbi/kW
Guangdong	*Implementing Rules for Market-based Demand Response in Guangdong Province (for Trial Implementation)*, 2022.4	Heavy industrial loads, commercial interruptible loads, customer-side energy storage, electric vehicle charging facilities, etc.	5% or more of peak load	Day-ahead demand response, interruptible load, competitive allocation of directly controlled flexible load	Centralized bidding price range: (1) Day-ahead = 70–3,500 renminbi/MWh (2) Interruptible load = 70–5,000 renminbi/MWh (3) Directly controlled flexible load = 0–40 renminbi/kW/month
Anhui	*Anhui Province Electricity Demand Response Implementation Program (for Trial Implementation)*, 2022.1	DR level ≥ 1 MW for industrial users; DR level ≥ 0.2 MW for commercial users; DR level ≥ 5 MW for load aggregators	5% or more of peak load	Day-ahead/intraday/real-time demand response	(1) Day-ahead/intraday peak shaving = 8 renminbi/kWh; (2) Real-time peak shaving = 12 renminbi/kWh (3) Valley filling = 3 renminbi/kWh
Guangxi	*Implementation Plan for Demand Response in Guangxi Electricity Marketization (Trial)*, 2021.12	DR level ≥ 0.2 MW and duration ≥ 1 h for electricity users, DR level ≥ 1 MW and duration ≥ 1 h for load aggregators	—	Day-ahead peak shaving	Centralized bidding price range = 0–2.5 renminbi/kWh
Hubei	*Implementation Program for Electricity Demand Response in Hubei Province (Trial)*, 2021.6	DR level ≥ 0.5 MW and duration ≥ 1 h for industrial users; DR level ≥ 0.2 MW and duration ≥ 1 h for other users	3%—5% of peak load	Day-ahead/intraday demand response	Centralized bidding price cap: Day-ahead = 20 renminbi/kW Intraday = 25 renminbi/kW
Zhejiang	*Notice of Electricity Demand Response Efforts for 2021*, 2021.6	Electricity users, load aggregators, etc.	Peak shaving = more than 200 GW (more than 5% of peak load)	Peak shaving/valley filling; day-ahead/hour-ahead, minute-ahead/second-ahead/response	≤ 4 renminbi/kWh, only in peak season
Shaanxi	*Work Program for Electricity Demand Response in Shaanxi Province in 2023*, 2021.5	DR level ≥ 0.2 MW for electricity users, load aggregators, etc.	Peak shaving: more than 4 GW (more than 10% of peak load)	Emergency/economy demand response	(1) Emergency peak shaving: 20 renminbi/kW for duration ≤ 1h; 30 renminbi/kW for duration > 1h (2) Economy demand response price cleared by centralized bidding with price cap: Peak shaving for nonresidential users is 10/15/20 renminbi/kW for duration ≤ 2 h, 2–4 h, > 4 h; Peak shaving for residential users is 5 renminbi/kWh; Valley filling for nonresidential users is 5–8 renminbi/kW for valley/flat period

RMI Graphic. Source: RMI analysis

Challenges and Outlook of Industrial DSF

Challenges of industrial DSF

Despite the large resource potential of DSF in the industry sector, the development and application of DSF still face challenges such as technological constraints, economic and market regulation, and enterprise management.[27] These challenges contribute to the current underdevelopment of industrial DSF resources.[28]

Challenges of technological constraints

The most basic condition for the development of DSF in industry is to clarify flexible load potential, response speed, response duration, and recovery speed of its demand response in order to make optimal decisions. However, the degree of digitalization, automation, and intelligence of equipment is still insufficient, and the information interaction interfaces of equipment with networking capability are not uniform yet. These technical deficiencies make it difficult to accurately assess the potential for industrial load flexibility.[29]

If smart devices are unable to capture key parameters that reflect production characteristics — or if there are no matched quantitative analysis and optimization models to utilize the key data — the demand response potential will not be effectively identified. This restricts the application of flexibility resources and impedes the effective management of demand-side resources.[30]

For some continuous production enterprises, the load stability of the production process is particularly important. If the duration and scope of the demand response cannot be accurately controlled, it may cause serious security risks. Conversely, for industries with complex production processes, demand response must meet the relevant production constraints, which are often manifested as nonelectricity variables. It is necessary to consider other production features besides load and to link these characteristics with industrial demand response, thereby establishing a controllable feature model that meets the production requirements.

In addition, the lack of technical standards is an important hurdle. Many industries are unfamiliar with baseline loads to ensure production quality and security, and they lack an understanding of demand response. Given the differences in the processes and technologies of different industries, there is heterogeneity in their demand response capabilities and characteristics. Unfortunately, this makes the experience of enterprises that have successfully participated in demand response nontransferable, further increasing the difficulty of scaling industrial demand response.

Challenges of economic and market regulation

Apart from technical challenges, it is clear that unsustainable business models and economic incentives are also important reasons for the slow development of industrial DSF.[31] From a cost perspective, DSF requires significant investments in technology and equipment, as well as additional operational costs. These costs are usually difficult to finance, making it challenging to promote demand response efforts. In addition, frequent demand response may affect the performance and efficiency of major production equipment and result in additional energy losses and reduced equipment lifetimes. In terms of benefits, the electricity cost within certain industries accounts for only a small percentage of total production costs. Relying only on load shifting and saving electricity costs will not bring significant improvements and may cause the risk of poor-quality products and project nondelivery.

The current low cost-effectiveness of demand response also reflects the absence of market mechanisms.[32] In terms of the electric energy market, only a few provinces such as Shanxi, Shandong, Guangdong, Gansu, and West Inner Mongolia have a spot market under long-period continuous trial operation. Industrial users of most provinces cannot directly observe the real-time changes in electricity prices, and this reduces their willingness to develop DSF and optimize the electricity use behavior. Although more than 18 provinces (municipalities and autonomous regions) have implemented plans related to demand response, most of them just complement orderly electricity consumption during the peak summer period.

The system needs of demand response and compensation standards are updated annually, which cannot provide stable investment signals for developing industrial DSF. There lacks a unified and comprehensive regulatory framework for DSF,and thus it is difficult for enterprises to implement the assessment and verification procedures on industrial DSF. Relevant demand response market mechanisms (trading varieties) still need to be refined and designed for different industrial load characteristics, response speed, response reliability, and other key parameters.

Fortunately, several provinces with faster power market reform progress have introduced market mechanisms for demand response and started regular operations. Since April 2022, Guangdong province has successively carried out the day-ahead invitation, interruptible load, competitive allocation of directly controlled flexible load, and other market-based demand response trading varieties. Gansu and Fujian have also issued relevant documents for trial operation, which have provided more opportunities for the development of industrial DSF.

Challenges of enterprise management

There are also enterprise management challenges for the implementation of industrial DSF. Senior leadership may be resistant to demand response practices due to a lack of knowledge about DSF. Conversely, demand response requires specific personnel with in-depth, specialized knowledge and imposes additional requirements on operating procedures, both of which can lead to employee resistance due to the need to learn new skills. These invisible barriers can make it difficult to develop industrial DSF.

Outlook for near-term efforts to promote industrial DSF

For China, it is important to help industries increase their awareness of DSF, clarify the strategic significance and economic benefit potential of participating in demand response, and identify the flexibility potential with accelerating digitalization and intelligentization of industrial production. Therefore, based on the current status of DSF in China, this report aims to summarize the patterns of industrial load, explore the demand response potential, and further identify the main challenges.

Subsequently, we will investigate the development potential, technological pathways, the demand response characteristics and their potential impacts, and the problems to be solved for major industries that are rich in DSF resources (e.g., aluminum, iron, and steel). Meanwhile, we will also present cases of DSF development in various industries around the world and summarize the practical experience that can be used as reference.

In recent years, a series of policies have been launched at the national and provincial levels to promote demand-side management, which has created opportunities for the development of industrial DSF.[33] The integration of information technology, artificial intelligence technology, and Internet of Things technology with traditional industrial process control and energy management systems has provided the necessary data and technological support for unlocking DSF.

Along with power market deregulation, the market mechanisms of demand response will be gradually established and improved, which provides economic incentives for industrial participation in demand response. The lean production, energy savings, carbon reduction, and participation in grid interaction of industrial enterprises is a systematic project. Consequently, the government should conduct top-level design jointly with multiple ministries to promote the high-quality development of the enterprise from a variety of dimensions in the post-industrial era. It is promising that industrial DSF will play a key role in guaranteeing the reliability and decarbonization of the power system in the near future.

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