Integrated Demand Response Characteristics of Industrial Park: A Review

Zhengqi Chen, Yingyun Sun, Xin Ai, Sarmad Majeed Malik, and Liping Yang

Abstract—**With the gradual upgradation of global energy consumption and the associated development of multi-energy sources, the pace of unified energy planning and design has been accelerated and the concept of multi-energy system (MES) has been formed. The industrial structure of industrial park (IP) consists of production and marketing of multi-energy sources, which makes IP become an ideal application scenario for MES. The coupling between multi-sources raises the complexity level of IP, which requires the demand side analysis in IP as it enables customers to actively participate in energy planning and development. This paper presents the concept and operation strategies of integrated demand response (IDR), and its model classification is analyzed in detail. Optimization model and IDR with varying time period are studied in IP to determine their impacts on the system. A detailed survey of different techniques in both operation strategies and model classification is presented and the classification is based on pros and cons. Finally, key issues and outlooks are discussed.**

Index Terms—**Industrial park (IP), multi-energy system (MES), integrated demand response (IDR), integrated direct load control (IDLC), demand side management (DSM), demand side comfort index.**

I. Introduction

In recent years, the focus of electric power industry has shifted towards the adjustment of energy structure, the reduction in fossil fuel emissions, the development and utilization of renewable energy and the improvement in terminal energy consumption [1]. The traditional energy supply system consists of electric power system, thermal system and gas system. With the rapid increase of the demand, a stable and sustainable power system is inevitable [2]. According to Danish energy planning, the electricity and heating industry will fully adopt renewable energy by 2035 [3]. The demand of efficient natural gas systems has also increased significantly over the years due to the stringent environmental protection measures. In general, these energy systems are designed independently and lack the coordination. Considering the optimization and coordination of different energy supply systems, the integration of industrial park (IP) in multi-energy system (MES) is one solution to this problem [4].

IP is a complex energy system that covers the production, conversion and utilization of different energy sources. Due to the diversity of IP energy, higher requirements are placed on the capacity allocation of multi-energy sources. Meanwhile, new challenges for demand response (DR) are set upon the dispatch of demand side, due to its large load demand, complex load characteristics, coupling of different energy sources and high reliability requirement of power supply [5]. Integrated DR (IDR) can not only solve the congestion of energy lines but also strengthen the balance of supply and demand. It can improve the market liquidity and guide customers to vary their energy demands. In addition, it can improve the efficiency and reduce the dependence on a single form of energy. As the world moves towards the smart cities which involve the integration of various energy sources, it is necessary to analyze the characteristics of IDR in IP. This can not only support the development of MES and IP, but also balance the supply and demand efficiently.

Currently, there are some researches on the demand side of IP. The demand side management mechanism of urban heating pipeline after the combination of electric heating network is studied in [3], in order to improve the system efficiency and alleviate energy supply congestion. By integrating consumers directly or indirectly as a resource into energy demand, the MES demand side can be integrated and utilized efficiently [6]. This provides a shortcut for efficient integration and unified planning of multi-energy sources in IP. According to [7], [8] considers the price and demand differences of various energy sources in the electric-thermal system and establishes the DR scheme and optimization model for the coupling system. A price-based control strategy for district heating networks is proposed in [9], but it is limited to thermal systems. The long-term unified planning of interdependent natural gas and power transmission systems is analyzed in [10]. An optimal dispatch model of power-gas integrated energy system is proposed in [11], which considers demand side load response and dynamic natural gas flow.

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All these studies are limited to one or two forms of energy and have not been extended to IP.

This paper presents an overview of the characteristics of IDR in IP. From the perspective of operation strategy, IDR can inhibit the demand, adjust the load curves and increase multi-energy conversion and multi-agent cooperation. From the perspective of model classification, according to the time period, IDR can be classified as short-term IDR and medium/long-term IDR. According to the optimization model, IDR is divided into integrated direct load control (IDLC) optimization model, price-based optimization model and game theory optimization model. The existing techniques are classified according to their advantages and disadvantages. Then, the discussion on the key issues and outlooks of IDR are presented.

The rest of the paper is organized as follows. Section II provides a brief introduction of IDR and its characteristics. In Section III, the operation strategy of IDR is analyzed considering the demand inhibition, load shifting, multi-energy conversion and multi-building coordination in IP. In Section IV, the model classification of IDR is analyzed considering the time scales and optimization model. The key issues and outlooks of IDR are given in Section V. Finally, the conclusion is presented in Section VI.

II. Concept and Characteristics of IDR in IP

As a new economic region, IP has a variety of loads such as cooling, heating, electricity and gas, as well as the conditions of comprehensive utilization of various energy sources. IP is an important scenario of multi-energy integration. The internal load demand of IP is large and its characteristics are complex, which requires high reliability of energy supply and more requirements for the operation and dispatching. Similar to the electric system, the demand of IP customer can vary in time, space and cost [12]. Based on the supply and demand characteristics, customers are encouraged to change their energy demand, and they will impact the supply and demand balance of different energy sources. At the same time, energy sources have different time response characteristics in demand scheduling, which is an important research direction in the future.

This paper mainly analyzes the characteristics of IDR in IP from four aspects: concept, operation strategies, model classification and key issues and outlooks of IDR.

This section extends the concept of DR to IDR and provides a brief introduction of IDR concept and characteristics. As shown in Fig. 1, some basic features of IDR are integrated and classified.

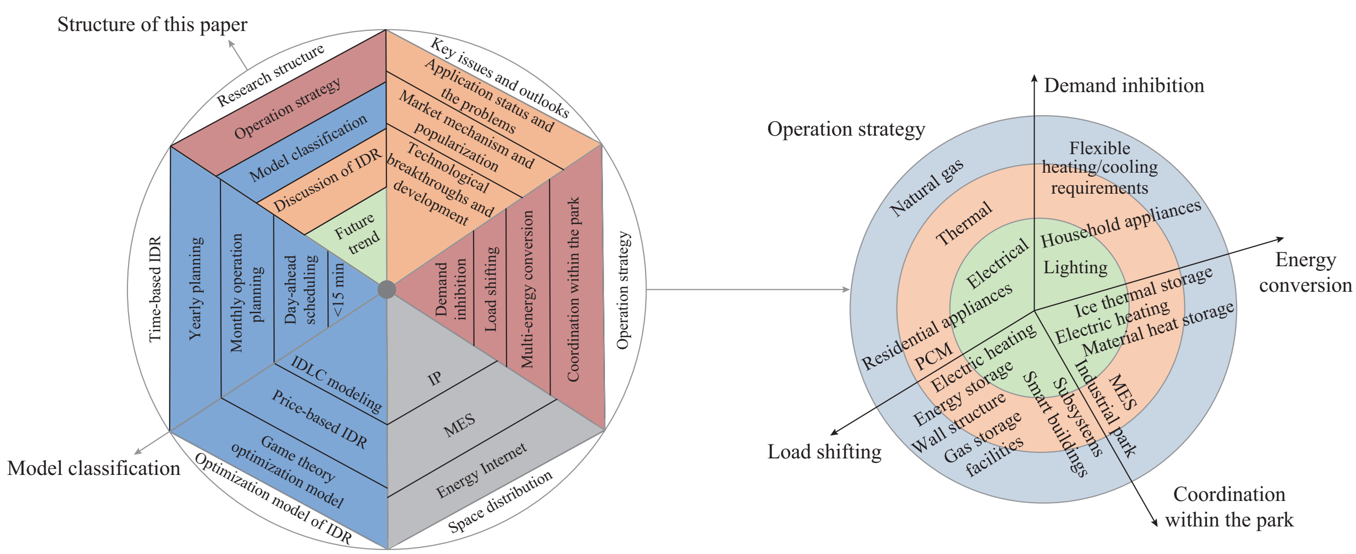

Fig. 1. Basic characteristics of IDR and extension of operational strategy in IP.

A. Concept of IDR in IP

IP is a platform between external energy systems and customers, covering the production, conversion and utilization of different kinds of energy sources [13]. It is limited for energy customers that the common DR cannot make full use of the interaction ability of different energy sources on demand side [14]. Therefore, IDR is suitable for complex energy management of IP. From the macroscopic view, the operation of future power grids is largely dependent on the integration of multi-energy networks [15]. IDR enables customers to use energy in a more flexible way and make full use of DR ability to regulate resources. The comparison between DR and IDR is shown in Table I. As shown in Fig. 2, with the expansion of IDR on demand side, IDR is able to manage customer requirements reasonably by integrating electricity with other energy sources, which realizes the deep integration of multiple energies and information flow on demand side. In fact, the coupling between different energy systems can be achieved through not only load shifting, but also the conversion of energy consumption sources [16].

B. IDR Characteristics in IP

The DR in traditional power system analyzes time as a dimension, and now IDR in IP adds multi-energy sources as another dimension. As a link between various energy sources, IDR breaks the barrier among different forms of energy, and its integration of energy has greatly improved the utilization efficiency of demand-side resources.

TABLE I
COMPARISON OF DR AND IDR

Category	DR	IDR
Application environment	Electric system	IP (electric system, thermal system, natural gas system)
Physical index	Voltage, current, angle, real/reactive power, resistance, reactance, susceptance	Temperature, pressure, transmission efficiency, air consumption, electrical output power, thermal output power, thermal/cooling output conversion efficiency
Operation strategy	Demand curtailing, load shifting	Demand curtailing, load shifting, energy conversion
Model classification	Control mode, time scale	Time scale, control mode, spatial dimension, energy forms

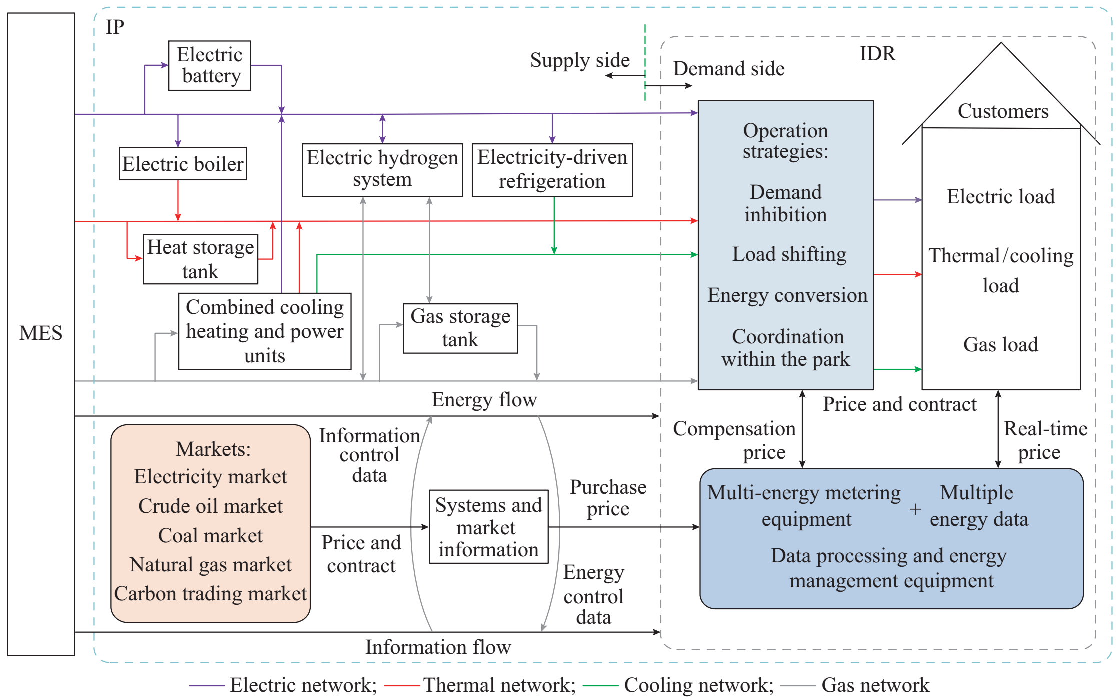

Fig. 2. Framework of IP and IDR.

Due to the complementarity of multi-energy sources, customers participating in the IDR program can provide more ancillary services for the energy system [17]. And improving the environmental benefits of the energy system is the extra value provided by IDR. Therefore, with the development of market economy and communication technology, it is extremely beneficial to promote the development of demand side resources towards IDR.

As shown in Fig. 1, some basic features of IDR in IP are integrated and classified. The structure of this paper is also included. The IDR operation strategies are simply classified and expanded. The IDR models fall into two types: time-based IDR model and control model. The present research status on IDR is discussed from four aspects in Section III.

III. Operation Strategies of IDR

Based on the concept of IDR and the supply-demand characteristics of IP in Section II, customers deeply participate in system regulation and energy markets. They reduce their energy costs by responding to price signals and incentives in multi-energy markets and adjust their needs and habits of energy usage according to the signals. The above characteristics of customers will affect the supply and demand balance on different energy sources. This section discusses IDR operation strategies from four aspects: demand inhibition, load shifting, energy conversion and multi-building coordination in IP as shown in Fig. 1. At the same time, the application scenarios of different strategies are analysed.

A. Demand Inhibition

Demand inhibition is one of the most important strategies in IDR. Demand inhibition is commonly used in home management or intelligent buildings including lighting system and flexible heating/cooling equipment [18]. Because these systems and equipment can be run at a more energy-efficient level during high-price periods.

According to the lighting index proposed in [19], on the premise of satisfying the customers, the lighting demand is adjusted according to the elasticity of electricity price, and the peak demand is reduced by 20% [18]. In [20], an optimized home energy management controller is proposed which incorporates ratings for several types of household appliances such as deferred, thermal and critical. This controller is based on dynamic price signal to reduce the consumer electricity charges and minimizes the daily energy consumption. The water supply temperature and thermostat settings can be optimized in intelligent buildings [21]. Based on the weather forecasting data and occupancy rate, the optimization problem aims to find the best indoor temperature setting points in different regions. In addition, the optimal water supply setting can also be determined, which minimizes the heat consumption and maximizes the customer's comfort. Game theory can be used to model the demand side management in coupling system [22]. Using Nash equilibrium can help decrease the total electricity demand and expenditure [23].

B. Load Shifting

The capacity of load shifting depends on the properties of energy. The time and effect of load shifting are different because of different energy sources. Therefore, load shifting can be applied to residential areas, energy storage systems, energy storage materials and energy networks. In addition, IDR can make full use of the natural storage capacity of the thermal and gas systems, and the remaining energy can be stored in the systems, which can be used later.

In residential sectors, 40% of the load is washing and dryer appliances. These appliances have great load shifting potential which can be easily rescheduled based on price signal without causing obvious customer's discomfort [18], [19]. Electric heating is one of the major contributors of residential demand [24]. Electric heating combined with intelligent energy storage such as water heaters, can shift energy consumption to off-peak hours without affecting the customer temperature. The goal is to optimize the consumption price of consumers and maximize the profits of retailers. Besides the energy storage potential of the appliances themselves, energy storage facilities can provide the main load shifting capacity and the capacity of storage is closely related to the degree of mismatch between energy production and consumption.

For the storage capacity of thermal, various phase change material (PCM) thermal energy storage systems have been developed over the past 30 years where the enhancement techniques are employed for effective charging and discharging of PCM thermal storage capacity [21], [25]. For residential heating applications, most phase-change problems are in the temperature ranging from 0 ℃ to 60 ℃. The influence of external melting ice on cooling characteristics of a thermal system is studied in [26]. However, the forms of optimal storage system, materials and regulation methods should be explored so as to match the power supply characteristics with the dynamic load. Due to the complexity of these technologies, it is difficult to compare and evaluate the capabilities of thermochemical regeneration and PCM. At present, these technologies are not widely employed in thermal systems.

The wall structure of the building and the transmission and distribution network have certain energy storage characteristics [27], [28]. The energy stored in a building depends on the thermal performance of the wall and the heating and ventilation system. The use of building structure for thermal storage is a key energy storage technology as it can improve the penetration of renewable energy and reduce the production and distribution problems [29]. In [28], the power shifting of energy storage is analyzed which has a great load transfer potential in cold weather due to the high heat demand and varying operational time. But a large number of heat pumps can limit the load transfer capacity. To enable the participation of residential customers in DR, space heat storage is proposed in [30]. The influence of storage on the optimal operation of heating system is also discussed but the system parameters are complex and there are many uncertainties.

Similar to thermal systems, the load shifting characteristics of gas systems are also associated with energy storage [31]. Natural gas storage facilities are usually connected to the transmission and distribution facilities. To ensure the adequate supply of natural gas and cope with seasonal load shifting and unexpected load surges, energy can be stored at non-peak hours [32]. This will also ensure the stability of the flow through the pipeline in the case of emergency. Gas storage facilities can improve the flexibility and utilization of existing pipelines. This can significantly reduce the system cost by eliminating the need for future large-scale construction of pipelines [33]. Natural gas storage facilities play an important role in maintaining supply in short-term operation and help prevent accidents that can affect gas delivery. Gas storage has a seasonal demand and it is stored in the non-heating season. Peak load storage facility is designed to provide fast response in a short period of time. The interdependence between natural gas network and power system security is discussed in [34] and a short-term storage model is proposed.

C. IDR Multi-energy Conversion

With the integration of various energy sources in IP, IDR enables customers to adapt to different energy price signals through flexible use of energy resources. On the premise of not affecting customer comfort, consumers can convert energy form such as electric, thermal and gas. Therefore, multi-energy conversion is generally applied in energy systems of buildings.

The energy conversion of IDR has been discussed in some literature. The ice thermal storage can be transformed into an intelligent load by a current spring [35]. This allows adaptive embedded load in energy system of buildings to respond quickly during transient demands. By developing thermal energy storage and electrical thermal technology, the energy service company may provide flexibility for each dwelling to cope with uncertainty [36]. Such an electrical thermal model is presented in [37] where power consumption is considered with the storage elements such as building materials and stored thermal energy. The thermal loads of a building can also improve the flexibility [38]. In an office building, accurate load management in rooms is influenced by thermal conditions and comfort level. The characteristics of building systems such as electric heating system and material heat storage, are important in coupling systems. A two-stage collaborative electric-gas optimization model is proposed in [39] to optimize the load forecasting. The safety of natural gas transmission and power systems can be evaluated by coordinated models [40]. The rotating charge regulation in gas and power systems is analyzed in [41], which also considers joint pricing method of natural gas and transmission network.

The customer's thermal comfort and day-ahead scheduling in coupling system are analyzed in Fig. 3.

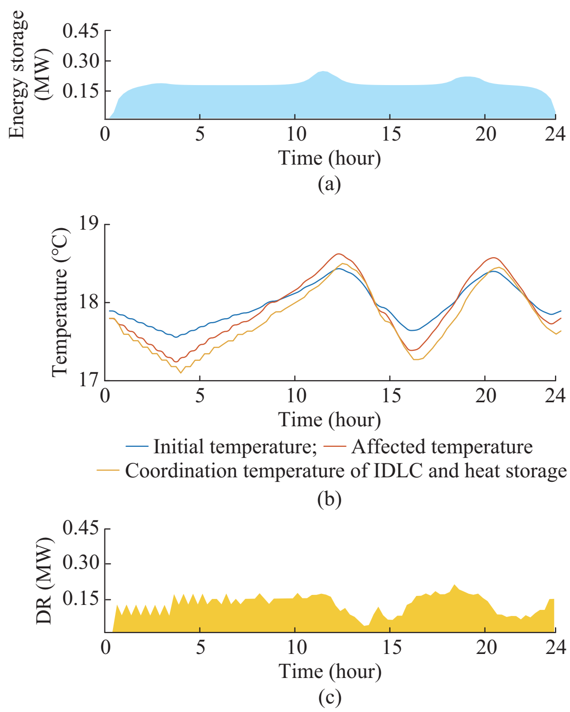

Fig. 3. DR and energy storage in coupling system to satisfy customer's thermal comfort.

The heating part is divided into combined heat and power (CHP) and gas heating. The heat demand side includes heat storage tank and natural gas heat pump to ensure rapid adjustment of heat demand fluctuations [42]. It can be seen in Fig. 3(b) that the average temperature affected by DR and energy storage is lower than the initial temperature, but still remains in the customer's comfort zone (17-19 ℃), which achieves the purpose of energy saving and also meets the constraints of customer's thermal comfort. Since the indoor thermal load has certain thermal inertia, DR and energy storage scheduling will move forward but the influence of temperature will experience a certain lag.

According to [43], large disturbances in power system operation will result in gas system failure. Since the heat stored in air is larger than that of electricity, the daily response of the gas subsystem can be made stronger and dynamic compared to the whole power system. In [44], a new optimal dispatch model of power-gas integrated energy system is proposed which considers demand-side load response and dynamic natural gas flow. It integrates the energy DR to optimize the electricity and gas load curve for the next day, exerting the complementary effect of different energy sources and improving the operation efficiency of the system.

D. Multi-building Coordination in IP

As a typical integrated energy terminal facility, intelligent building can be regarded as a unit that involves the conversion, consumption and storage of different energy needs. But the demand capability and dispatching capability of a single building are limited, so it is difficult to directly participate in the energy market. Therefore, the demand aggregation of multi-building in an IP has the possibility of demand dispatching [45]. In [46], the model of co-operation optimization of multi-building is studied which minimizes energy consumption and reduces complex network operation. In the model, energy exchange is also considered. A price mechanism is proposed to ensure the fair operation of multi-building. Reference [47] proposes a system architecture for load balancing and DR management of intelligent buildings, classifies control strategies and load structures, and a multi-layer control method is proposed to analyze the DR of intelligent buildings.

Table II summarizes the operation strategies of this section and analyzes the merits and weaknesses of each section.

TABLE II
TECHNIQUE, ADVANTAGES AND DRAWBACKS OF IDR OPERATION STRATEGY

Model	Potential advantage	Potential drawback
Demand inhibition [18], [20]-[23]	Better predict the behavior of the system; reduce load demand and improve economy	Difficult to compare and evaluate the applicability to specific applications; technology is complex; sacrifice some customer's comfort
Load shifting [21]-[29], [32]-[34], [48], [49]	Store at non-peak to relieve peak load; improve the penetration of renewable energy and overall energy storage; improve the efficiency and economy	Delay depends on the characteristics of building and the calculation is complex
Multi-energy conversion [35]-[44]	Improve the flexibility and reduce the over construction of pipelines; prevent accidents	Cope with seasonal load shifting; quick output capability in a short period of time
Multi-building coordination in IP [45], [46], [70]	Multi-building coordination	Single building is difficult to participate in the energy and market

IV. MODEL CLASSIFICATION OF IDR IN IP

Based on the analysis of Section II, the model classification of IDR in IP can be analyzed from the perspectives of time, control mode, space, energy form, etc. This section discusses IDR classification from two main perspectives of time-based IDR and optimization model of IDR.

A. Time-based IDR

Traditional DR can operate in multi-time scales of the power system in response to market price and incentive signals. Because IDR integrates multi-energy sources, research on multi-time scales becomes more complicated. Taking natural gas as an example, according to the annual international energy trend, the price fluctuates every year or even every quarter, which has a significant impact on the signing of long-term natural gas contracts and the dispatching of natural gas demand. Therefore, IDR analysis for multi-time scales in IP is essential. In this paper, IDR is classified as short-term, and medium/long-term IDRs according to the time period. Figure 4 gives a simple classification of IDR characteristics on time scales.

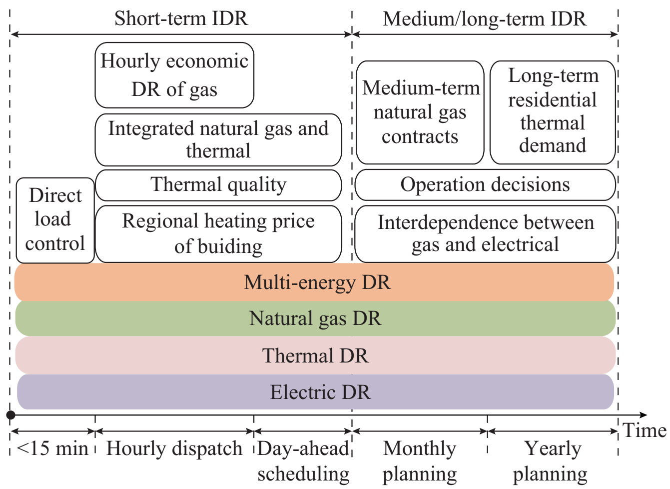

Fig. 4. IDR characteristics on time scales.

1) Model of Short-term IDR

Short-term (48 hours ahead) forecasting is necessary for dynamic online optimization of load control, market transactions and distributed network operation in future energy systems [23].

A comprehensive model for short-term thermal load prediction and control response is studied in [48]. Based on regional heating price, the temperature setting value for the next hour can be predicted which increases the flexibility of heat load [19]. The utilization of building's thermal quality provides great potential for short-term adjustment of total power consumption. In order to evaluate the relationship between the flexibility of the thermal system and the power generation system in short-term DR, active DR (ADR) is proposed which may bring many benefits [48]. An energy hub model combining renewable energy, storage and DR is established in [23] to achieve short-term energy economic dispatch.

The short-term load fluctuations in natural gas system can be caused by meteorological variations, holidays, social activities, enterprise maintenance or shutdown. Accurate load forecasting is very important for dispatching gas supply enterprises. Hourly economic DR can provide a variety of security options to operators [49]. A coordinated dispatching problem between hydrothermal and natural gas transmission system can be solved by the augmented Lagrange relaxation method [50]. The aim is to minimize social costs by coordinating hourly schedules and supplying natural gas for load or power generation. A security constraint unit commitment model is proposed in [51]. This model improves the operational reliability and economy of the integrated power and natural gas system. However, it is only suitable for short-term economic dispatch and does not consider medium/long-term scheduling of natural gas system. In [52], an optimal day-ahead scheduling model considering power-to-gas (PtG) storage is proposed. The situation of insufficient gas supply and power outage in PtG system is studied to establish demand optimization management mechanism for natural gas systems. But the unified planning mechanism for multiple forms of energy is not discussed.

The operation and planning of integrated natural gas and hydrothermal power generation systems are discussed in [53] where the linear gas transmission is a constraint. To solve this, a double decomposition method based on Lagrange is proposed that adopts dynamic programming. In [54], a demand side customer complementary aggregation response model based on multi-energy sources is proposed as well as an optimal two-stage short-term dispatching strategy. By using price mechanism to guide the aggregation of different types of customers, the demand side still maintains good responsiveness without changing customer's comfort.

2) Model of Medium/long-term IDR

Medium/long-term planning covers months or years and is generally influenced by seasons and policies. In this regard, different techniques have been proposed for both thermal and natural gas systems.

A linear marginal cost model is used in [55] which optimizes the long-term hydrothermal unit dispatch. The compound marginal cost function of the thermal system is incorporated in the model, the aspect of reliability can also be integrated into this model to provide information on long-term operation decisions [56]. The long-term effects of generation variables and demand-side flexibility on thermal power generation are studied in [57]. This study combines three models: generation planning model, unit commitment model and economic dispatch model. Research shows that demand-side elasticity can make up for the smaller slope of net load more economically and effectively. Improving the integrity level of residential thermal demand has reduced the potential of DR, but energy consumption has declined considerably. This has been proved beneficial in long term [58].

In [33], a cooperative optimization programming model is proposed that considers the long-term interdependence between natural gas and power system. The medium-term planning and financial risks are significantly affected while considering the natural gas contracts and constraints [59]. In [60], the storage of cascaded reservoirs is aggregated into a single composite reservoir, which reduces the number of state variables studied over a long period of time. This will be beneficial for future market structures and investment plans.

B. IDR Optimization Model

This section focuses on the optimization model of IDR. The control mode of IDR can be divided into IDLC, price-based incentive control and game theory optimization model. IDLC allows operators to control the load directly and improves customers' satisfaction through the compensation mechanisms. The price-based control guides customer behaviors depending on the price. The game theory optimization model provides optimal strategies for IDR implementation.

1) IDLC Optimization Model

A careful analysis of IP background reveals that DR will gradually develop into IDR. Similarly, DLC can be extended to IDLC. Its purpose is to achieve load transfer and reduction, and therefore minimize the total cost [47]. The benefits of IDLC energy saving can be described in terms of cost as:

$$C^{\mathrm{IDLC}}(t)=\sum_{t=1}^{T}\sum_{k=1}^{N_{\mathrm{IDLC}}} b_{p,h,k}^{\mathrm{IDLC}}(t)\,P_{k}^{\mathrm{IDLC}}(t) \tag{1}$$

where C^{IDLC} is the running cost of IDLC of MES at load side; P^{IDLC} is the active contribution of IDLC; N_{IDLC} is the number of integrated load control groups; and b^{IDLC} is the compensation price of IDLC; p,h,k represent the power system, thermal system and group number, respectively. Based on the Weber-Fechner law, a psychological activity model of customers participating in IDLC can be constructed. It can be used to construct a reasonable and effective pricing scheme to satisfy customers' psychological expectations during demand-side scheduling [42]. In (1), $b_{p,h,k}^{\mathrm{IDLC}}(t)$ is real-time IDLC compensation price, which is related to the real-time purchase price as:

$$b_{p,h,k}^{\mathrm{IDLC}}(t)=b_{p,h,k}\ln\left(c_{p,h,k}(t)\right)+C \tag{2}$$

where $b_{p,h,k}$ is the compensation coefficient (normally 0.5); $c_{p,h,k}$ is the real-time price of power system and thermal system; and C is a constant. According to the scheduling requirements, the load can be divided into M groups. The load of DLC during the period t can be expressed as:

$$P_{k}^{\mathrm{IDLC}}(t)=\sum_{k=1}^{N_{\mathrm{IDLC}}}\alpha_{k}(t)\,P_{k}(t) \qquad \alpha_{k}(t)\in[0,1] \tag{3}$$

where $P_k(t)$ is the load power regulated by IDLC in group k during period t; $\alpha_k(t)$ is the regulation rate, $\alpha_k(t)>0$ indicates increased load regulation and $\alpha_k(t)=0$ indicates stop load regulation. There is no accurate mathematical model for energy payback (EP) and a three-stage autoregressive model is widely used for fitting as [61]:

$$P_{pb,k}(t)=\alpha P_{k}(t-1)+\beta P_{k}(t-2)+\chi P_{k}(t-3) \tag{4}$$

where $P_{pb,k}(t)$ is the energy payback of the group k in period t; $P_k(t-1)$, $P_k(t-2)$, $P_k(t-3)$ are the IDLC controlled loads of group k at $t-1$, $t-2$ and $t-3$ periods, respectively; and α, β, γ are the coefficients of payback.

Figure 5 shows the result of the IDLC where the IDLC comprehensive optimization model is based on (1)-(4). It can be seen that from hour 8 to hour 11, the participation of IDLC significantly reduces the peak load. A similar trend is also observed from hour 15 to hour 22. During this time, the energy efficiency of IDLC can reach 6.23%. The regulation time is 15 min. The rebound trend is consistent with the controlled quantity but the time is delayed in the controlled quantity. The peak value of the rebound quantity is smaller than the controlled quantity. However, it is necessary to formulate a clear control strategy, to sign relevant contracts before controlling and to establish the compensation mechanisms in order to achieve the above effects.

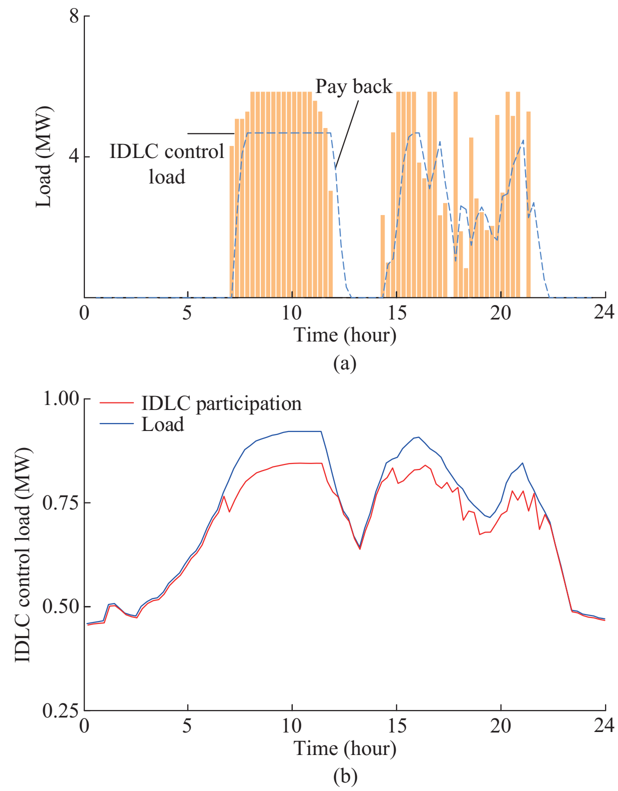

Fig. 5. Power load and IDLC controlled curve. (a) Curves of IDIC and pay back load change. (b) Curve of IDIC participating in load dispatching.

2) Price-based IDR Optimization Model

At present, consumers of electric-thermal loads consume a fixed amount of electricity but with the advent of real-time monitoring and advanced communication technologies, a portion of electricity consumption can be postponed to off-peak time periods.

For instance, real-time price signals are used in [62] to optimize the energy storage of electricity. The goal is to shift the charging time to a more optimal instance to maximize the profit of the retailer. In [63], the concept of optimal load dispatch is extended from electric power system to the electric thermal coupling system with the day-ahead tariff. The characteristics of different pricing mechanisms are analyzed in some techniques and real-time pricing is adopted to attract consumers. For instance, [64] summarizes the existing pricing methods and heat price models and provides advanced pricing mechanism for the distribution heat network (DHN) system. Marginal cost is regarded as a pricing method of DHN [64], [65]. The industrial energy efficiency measures for local DHN suppliers are beneficial to both industry and environment.

Small changes in indoor temperature do not affect customer's comfort. According to the Danish Standard DS474-1993-Norm, the indoor temperature change should be within 2 °C/hour [66]. The price-based control strategies can be integrated with the comfort of customers. Similarly, optimization techniques can be employed to solve the problem where the objective is to shift the load to a period of low marginal cost [67]. To achieve this, the daily price has to be broadcasted to each customer and substation. Consequently, without deviating from the comfort zone, energy cost savings can be used as an incentive to encourage end-customers.

To encourage heating charges for storage equipment at night, some tariffs for time of use (ToU) have been set. Some other scheduling techniques include price-based program (PBP) such as real-time pricing (RTP), which allows customers to make more economical improvements in the charging of water heaters. A model predictive control (MPC) of space heating is studied in [68] which uses RTP and CO_2 intensity signals. The concept of ADR can also be used to track real-time price signals and outdoor temperature changes [69], [70], which reduces electricity cost and peak demand and maintains customer's comfort. With the introduction of electric-thermal-gas market mechanism, it is important to consider the combined pricing of natural gas and transmission network for the unified planning of energy network.

Table III summarizes the model classification in this section and analyses the advantages and disadvantages of each model.

TABLE III
TECHNIQUES, ADVANTAGES AND DRAWBACKS OF MODEL CLASSIFICATION OF IDR

Model	Potential advantage	Potential drawback
Short-term IDR [27], [31], [34], [48]-[54]	Short-term economic dispatch Minimize social costs Important for dispatching of supply enterprises Increase flexibility	Require higher control and communication level Affected by holidays, meteorological, maintenance, and other factors
Medium/long-term IDR [33], [55]-[60]	Have certain reliability Decline energy consumption Bring long-term advantages to investment companies	Need system flexibility Long-term research has more variables
IDLC [42]-[73]	Load transfer and reduction, minimize the total cost	Control strategy or sign contracts before control Compensation mechanism
Price-based IDR [61]-[68]	Build a future energy price Provide advanced pricing mechanism Postpone the charging time to a more optimal time	Customer comfort degree is not considered
Game theory optimization model [71]-[75]	Provide optimal strategies for IDR implementation Suitable for multi-agent strategies in IP	Require higher control and communication level Research is not deep enough

3) Game Theory Optimization Model of IDR

Since IDR in IP involves multiple forms of energy, the coordinated use of multi-energy sources and the balance between supply and demand are multi-agent coordination issues. The application of game theory optimization can provide optimal strategies for IDR implementation.

At present, the research on the game theory optimization model contains a game solution for multi-agent to participating in network congestion based on game theory in [71]. When load demand increases dramatically, this method may avoid network congestion effectively. It classifies the load groups, uses game theory to analyse the scheduling between groups, and determines the optimal equilibrium strategy between the supply and demand sides in energy trading in [72]. In [73], it is proposed to manage energy consumption based on non-iterative Stackelberg model and historical real-time pricing, and transfer peak load through DR technology. In [74], it is proposed that the energy supply side has set the price and the number of transactions, while the consumption of demand side needs to meet the contract as much as possible. However, a large number of uncertainties on the demand side require the DSM to meet the contract as much as possible. The closer the DSM is to the contract, the higher the reward is. In [75], a phase change heat storage capacity optimization configuration model based on cooperative game is proposed. Furthermore, a quadratic profit distribution scheme based on the shapely value distribution model is proposed to construct a fair and reasonable profit distribution mechanism.

V. KEY ISSUES AND OUTLOOKS OF IDR

A. Application Status and Problems of IDR

On the energy supply side, firstly, the implementation of IDR can delay or reduce the construction cost of the energy supply side and improve the ratio of equipment comprehensive utilization. Secondly, IDR can give full play to the benefits of multi-energy replacement, enhance the overall efficiency of energy sources, and stabilize the volatility of multi-energy supply and reduce the cost of balanced regulation and carbon emission of the system. Nevertheless, the previous research has few economic analyses on long-term planning. In addition, lots of papers only analyze the energy supply side planning without considering IDR. The supply-load planning considering comprehensive energy sources of IDR can be further studied.

On the demand side, the implementation of IDR enables customers to respond to price signals in multi-energy markets and adjust their energy demand and consumption habits [46]. Customers can be guided by IDR to formulate reasonable comprehensive energy utilization schemes. In the meanwhile, IDR brings other benefits, including improving energy efficiency on the customer side, reducing energy consumption costs of customers, and obtaining additional economic benefits [45]. Sometimes, the optimization results will increase the total energy cost of households and affect the enthusiasm of customers to participate in IDR, which reflects the difference between customers and energy companies in optimization goals shown in Table II [75]. At present, less attention is paid to the co-optimization of customers and energy companies on demand side. It is the focus of future research on how to coordinate the interests of many parties to achieve a mutualism market mechanism.

The differences between the individual needs of the customers and the privacy of the customer energy-using behaviors may interfere with the optimization decisions of the IDR. It is difficult to achieve a unified grasp of the customer operating state [76]. It also can be seen from Table III that the present research on multi-agents in IPs of IDR is not sufficient enough, including the optimization of multi-energy sources coordination among multi-agents and unified optimization through centralized or distributed methods.

B. Market Mechanism and Popularization of IDR

IDR not only integrates multi-energy sources, but also provides integrated ancillary services. IDR can analyze the coupling characteristics among different energy sources, optimize production characteristics, and develop an optimization adjustment schedule for customers of large-scale industry. IDR is able to provide investment analysis and consultation for energy conversion equipment to investors and commercial customers as well. For the operating services of IP, it can assist the market to adjust the energy utilization curves, regulate the peak load and frequency, and build a comprehensive market mechanism of integration for IP.

For the popularization of IDR, according to the successful experience of DR business model in the US, the unbundling of sales and revenue of energy companies and the introduction of third-party curtailment service providers (CPS) are key factors in promoting DR project operation. At present, energy companies in China only promote DSM through certain administrative means. Meanwhile, integrated CPS (ICPS) companies participating in IDR projects are still rare in China. Therefore, it is necessary to develop such companies from the aspects of policies and funds. Moreover, the roll out of revenue unbundling mechanism in energy companies should be accelerated, in order to accelerate the development of IDR projects in China.

C. Technological Breakthroughs and Development of IDR

1) Development from Macroscopic View

1) Establishment of multi-time scales and multi-level scheduling strategies in IP

It can be observed from Table II that IDR can be divided into short-term IDR and medium/long-term IDR. Since the structure and response speed of energy systems are different, various time scales are used to deal with various forms of energy structure and demand characteristics. Therefore, building the multi-time scale scheduling strategy is particularly important for MES. The construction of such a scheduling strategy will not only optimize the mismatch between scheduling time and energy response, but also coordinate the allocation of large-scale clean energy access.

Meanwhile, due to the complexity between different forms of energy in MES and customer characteristics, it is necessary to construct multi-level scheduling strategies such as terminal customer scheduling strategy, building-based scheduling strategy, distribution network or regional scheduling strategy. These schemes can be integrated with MES. This will extend the cooperation between multi-time scale scheduling strategies and help coordinate dispatching demand side resources according to different levels of energy usage and time scales.

2) Establishment of multi-energy-advanced metering infrastructure (AMI) system

Similar to AMI in power system, the construction of multi-energy-AMI, which belongs to IP, can be used as a network processing system for measuring, collecting, storing, analyzing and utilizing customer energy information. It consists of intelligent acquisition terminals and communication devices installed at the customer end. At the same time, multi-energy-AMI can consider market prices, real-time energy demand and customer behavior to construct a detailed business model.

3) Establishment of internet cloud storage system

IP has various complex uncertainties. Multiplicity is reflected in the fact that uncertain sources exist in the production, transmission and consumption of electricity, heat and gas. These uncertainties may be continuous, discontinuous or time-varying. Complexity occurs in correlation between various uncertainties, and the flexibilities of different systems are also different. In addition, electrical-thermal and thermal-gas energy storages are only used in building systems, but not extended to large-scale systems. Unified planning and scheduling of cloud energy storage will adapt IP and IDR to suit applicability and flexibility.

2) Technical Support of IP

1) Establishment of the demand-side comfort index integration platform

Customer's comfort is a very important indicator of demand side scheduling. Demand scheduling generally requires improving system reliability and balance between supply and demand to meet customer safety and comfort index. For example, thermal supply requires that the customer indoor temperature be comfortable even if the external temperature is uncertain. Future research should focus on customer's comfort in MES as it can meet the scheduling requirements and at the same time, improve customer satisfaction.

2) Analysis of IDR reliability

IDR can promote the switching and cascade utilization of energy at different levels and periods, and improve the overall efficiency of the system. When the supply and demand of a kind of energy fail or energy shortage occurs in individual periods, IDR encourages customers to supplement energy in different periods with the method of conversion of different energy sources so as to improve the reliability of energy supply of the whole system. However, the participation time and approaches of demand side in IDR are uncertain. For example, the random participation of large industrial users in IDR will have a greater impact on the security of the energy supply network. It is necessary to analyze the impact of the randomness of IDR on safety and reliability through quantitative calculation of integrated energy network flows [75].

The current study focuses on IDR participation in dispatching and exploring demand-side flexibility to compensate for uncertainty and network operation economy, with less analysis of IDR's own uncertainty and its impact on the safety and reliability of comprehensive energy network. There is little analysis on the impact of IDR for key factors of energy supply reliability such as grid frequency, voltage, natural gas pipeline pressure, heat grid temperature.

VI. Conclusion

This paper presents an overview of IDR characteristics of IP. Firstly, we discuss IDR operation strategies from four aspects: demand inhibition, load shifting, energy conversion and multi-building coordination in IP. Then, the model classification of IDR is analyzed considering time scales and optimization model. According to time period, IDR can be classified as short-term IDR and medium/long-term IDR. And the IDR optimization model is divided into IDLC optimization model, price-based optimization model and game theory optimization model. Thirdly, the key issues and outlooks of IDR are discussed from three aspects: the application status and the problems of IDR, the market mechanism and popularization of IDR and technological breakthroughs and development of IDR.

The advantages of IDR include inhibiting demand, adjusting the load curve, allowing operators to control the load directly, improving customer satisfaction through the compensation mechanisms, guiding customer behaviors depending on the price and providing optimal strategies. Nevertheless, the previous research has little economic analysis on long-term planning. The market mechanism is not perfect, and IDR is not used widely yet. In addition, IDR needs the technological breakthroughs from the perspectives of both reliability and comfort index.

Based on the review, we believe that IDR can provide an opportunity to customers to participate in IP operation which will not only increase the system flexibility and reliability but also provide more choices to customers. As a link between various energy sources, IDR breaks the barrier among different forms of energy, and its integration of energy has greatly improved the utilization efficiency of demand-side resources. This will be especially beneficial in future smart cities where different sources of energy are brought under one roof.

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