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A review on modelling methods, tools and service of integrated energy systems in China

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Abstract

An integrated energy system (IES) is responsible for aggregating various energy carriers, such as electricity, gas, heating, and cooling, with a focus on integrating these components to provide an efficient, low-carbon, and reliable energy supply. This paper aims to review the modeling methods, tools, and service modes of IES in China to evaluate opportunities for improving current practices. The models reviewed in this paper are classified as demand forecasting or energy system optimization models based on their modeling progress. Additionally, the main components involved in the IES modeling process are presented, and typical domestic tools utilized in the modeling processes are discussed. Finally, based on a review of several demonstration projects of IES, future development directions of IES are summarized as the integration of data-driven and engineering models, improvements in policies and mechanisms, the establishment of regional energy management centers, and the promotion of new energy equipment.

1. Introduction

With the development of energy-intensive economies and the large-scale emission of greenhouse gases (GHGs), building an efficient, reliable, and low-carbon energy system has become the core solution to addressing resource scarcity, environmental pollution, climate change, and other challenges. In the process of achieving global low-carbon transformation, developed countries, and regions such as the United States, Japan, Canada, and the European Union have formulated climate strategies, committing to achieving net zero carbon dioxide emissions by 2050. In September 2020, China also announced its goal of striving to reach the peak of carbon dioxide emissions by 2030 and achieving carbon neutrality by 2060. However, China's energy transformation is facing challenges such as slowing demand, excess traditional production capacity, prominent environmental problems, and low efficiency. To fully utilize the complementary nature of multiple energy resources and improve energy efficiency, it is urgent to establish a complete energy system [1]. Integrated energy system (IES) is an energy system that can unify the planning and scheduling of various energy sources such as electricity, natural gas, heat, and cooling, and it is of great significance for promoting energy structural transformation and driving energy revolution.

The IES encompasses the production and conversion of various energy sources, such as electricity, thermal energy, cooling energy, gas, as well as energy storage equipment, renewable energy equipment, and energy networks. This system can be implemented at different scales, from individual buildings to communities, regions, cities, countries, and even international levels [2]. Currently, research on IESs in China mainly focuses on the regional and local levels. Figure 1 illustrates the basic structure of a typical regional IES.

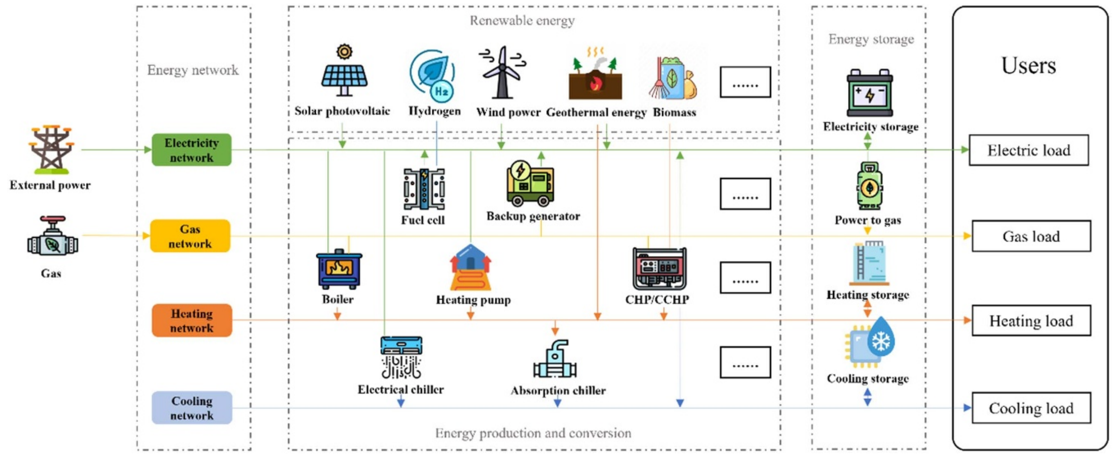

Figure 1. Schematic diagram of a regional integrated energy system.

The IES emphasizes planning and operation to achieve the complementary advantages of the energy system, making energy production, conversion, and transmission greener, more efficient, convenient, and reliable. It is a typical modeling challenge to optimize such a system across multiple scales in both design and operation stages. First, IES models are complex, computationally expensive, and require multiple disciplines in model development. Then, the planned and operated on time scales of IES ranging from one day to several years or even decades, and the planning scale varies from terminals to cities or even countries. Such a large time–space span also leads to a lot of challenges to the research of IES. In a large spatial span model in China, regional differences in energy demand for different departments need to be considered. This requires that IES research is not just limited to the static energy supply system, but also needs to simulate dynamic energy demand and explore the interaction between the energy supply and demand.

Additionally, with the rise of IESs, integrated energy services have gradually become one of the important paths for China's urban energy transformation and upgrading. Integrated energy services refer to the mode of directly providing users with energy services such as cooling, heating, and electricity through IESs, which aims to meet different requirements of users for energy quality, variety, and supply time [3]. Integrated energy services can promote the deep interaction among generation, transmission, load, and storage, connecting users, grid companies, gas companies, equipment suppliers, and integrated energy service providers, and promoting hierarchical utilization of multiple forms of energy to provide users with diversified services such as multiple energy supplies and distributed power generation. However, currently, integrated energy services in China are still in the early stages of development, and there are problems such as immature commercial modes, the need for further deepening of institutional mechanism reform, and the lack of high-standard demonstration projects.

Many studies have previously concluded the current state of development of IES worldwide. However, the specifics of the modeling and implementation of IES in China are not yet clear. In this article, different integrated energy models are classified into demand forecasting models and energy system optimization models. Then, load forecasting methods and a typical optimization modeling progress for IES are presented. In addition, the functional characteristics and applicability of several domestic simulation and planning tools and demonstration projects for IES are summarized.

The rest of this paper is organized as follows. Section 2 describes the modeling methodology of IES. Section 3 presents typical integrated energy model tools and platforms in China. Section 4 introduces status and development of integrated energy services in China. Section 5 gives several domestic demonstration projects for IES. Section 6 provides some summary and evaluation of the opportunities and barriers to improve current IES practices.

2. Modeling methodology

2.1. Demand forecasting

Accurate prediction of the load of the IES is an important part of the planning and operation of the system, and it is also a fundamental prerequisite for ensuring the stable, reliable, and economical operation of the system. Domestic scholars have conducted extensive research on load forecasting of the IES. It has evolved from the development of a single energy type, and with the accelerating penetration rate of new energy and the continuous expansion of application scenarios, the load forecasting of IES is also developing toward multiple load type.

2.1.1. Load forecasting for a single energy type

Currently, considerable progress has been made in the load forecasting of a single energy type. There is extensive research on the electricity load forecasting, which can be divided into short-term, ultra-short-term, and medium-to-long-term prediction according to the time scale [4, 5]. Existing prediction methods mainly include support vector machines, long short-term memory (LSTM), back propagation (BP), neural networks, artificial intelligence, big data cloud computing, and various combinations [6, 7]. Depending on the specific prediction object, suitable methods or combined methods can be selected. Yang *et al* [8] proposed a comprehensive probability density prediction method based on Gaussian process component regression, considering weather conditions, electricity prices, calendar information, and historical load data. Zhifeng *et al* [9] proposed a probability density prediction method based on deep learning, with the consumer price index as the target factor, considering residential electricity consumption factors, date-related factors (such as month, day, and season data), air quality-related factors (such as PM2.5, SO_2, CO, etc.), weather-related factors (such as rainfall level, daily temperature, etc.), and economic factors (such as the impact of economic models on residents' living standards). Research and application of heat load forecasting mainly aim to achieve the economic operation of the heating system under the condition of ensuring the actual heating demand of heat users (heat substations), and to achieve energy conservation and emission reduction. The main application scenarios are also focused on centralized heating scenarios, similar to the electricity load prediction methods, mainly using computer tools such as least squares, BP neural networks, and machine learning [10]. Xuan *et al* [11] considered historical load data and weather conditions, and constructed two commercial building cold load prediction models using chaotic support vector regression (SVR) algorithm and wavelet decomposition(WD)-SVR algorithm. In terms of natural gas load prediction, Gejirifu and Wangfeng [12] used the adaptive boosting-particle swarm optimization-extreme learning machine (AdaBoost-PSO-ELM) comprehensive learning method to construct a gas consumption prediction model with economic growth, population, resident consumption, and import dependence as the core factors.

2.1.2. Load forecasting for multiple energy types

Building upon research on load forecasting for a single type of load, there are currently two main research directions on load forecasting for multiple energy types [13]. One is the traditional single-model prediction methods, such as utilizing an improved LSTM model to enhance multi-load prediction accuracy [14], conducting correlation analysis on electric, gas, and thermal loads using association theory [15], or using the Pearson correlation coefficient to 'pixelate' various types of basic load units with no clear pattern before inputting them into LSTM [16]. Traditional electricity load forecasting methods, such as wavelet neural networks [17], least square support vector machine regression [18], generalized regression neural networks [19], have also been widely used in comprehensive energy load forecasting. In addition, computer technology that has been increasingly researched in recent years is rapidly being applied to comprehensive energy load forecasting. Fengzhang *et al* [20] first analyzed the correlation between various factors that affect multi-load, and proposed a deep learning model that combines convolutional neural networks and SVR to achieve multi-load prediction for cooling, heating, and electricity loads. Another research direction is the feature decomposition-based multi-layer combined prediction method, where the types of multi-loads are first decomposed based on their correlations, and the individual components are predicted before the results are combined and reconstructed for multi-load prediction. Shoumao *et al* [17] utilized the variational mode decomposition method to decompose the load sequence of the comprehensive energy system, constructed different feature sets with meteorological information, and predicted them using SVR and LSTM models separately before inputting them again into SVR to form the final prediction. Compared with actual data, the prediction accuracy was improved. Jinpeng *et al* [21] conducted further decomposition on the first-mode components and used neural networks for prediction.

2.2. Energy system optimization

The focus of the energy system optimization is on the planning and operation of the IES system. In the long-term evolution of energy systems, these models are commonly used to find installed capacity and operating modes, while striking the equilibrium between energy production and external consumption.

The energy system optimization model are usually developed by different approaches, including top-down and bottom-up. The top-down approach relies on statistical data to express the relationship between energy demand, energy supply and related drivers (e.g., socioeconomic and climatic variables). Since this approach relies on easily available aggregated historical data and generally does not involve detailed technical descriptions, it is widely used in urban energy researches. Perera *et al* [22] introduced a data driven

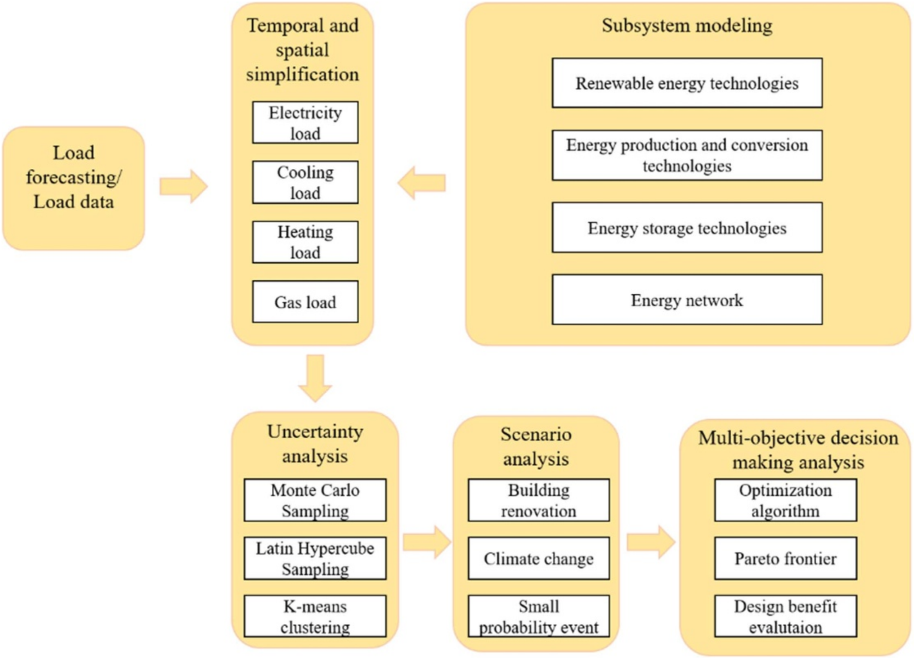

Figure 2. A typical optimization modeling progress for IES.

approach based on reinforcement learning to design distributed energy systems. The results revealed that data-driven models are capable to conduct design optimization of complex energy systems. Chao *et al* [23] proposed a data-driven power system planning framework that considers shorter-term (e.g., hourly) uncertainties using robust optimization and the scenario approach. Dongqi *et al* [24] collaboratively released an open-source extendable model that is synthetic but nevertheless provides a realistic representation of the actual Texas electric grid, accompanied by open-source cross-domain data sets, which could quantitatively assess the impact of various policies on mitigating the impact of extreme events. However, the effectiveness of the top-down modeling approach heavily depends on data availability, which is currently limited in China. The lack of publicly accessible or readily available design and operational data for energy system optimization provided significant challenges to the application of data-driven modeling methods. As a result, the subsequent sections predominantly concentrate on bottom-up modeling approaches and provide an overview of research cases in China.

Bottom-up approaches perform detailed simulation of equipment use and energy demand. Detail simulations of equipment operation and energy use is required, and this method is suitable for specific system design and planning. Optimization techniques like linear programming (LP), mixed-integer linear programming (MILP) or mixed integer nonlinear programming (MINLP) can be used to retrieve the investment, production, and consumption patterns in order to minimize cost and environmental emissions [25]. By aggregating the needs of different regions, energy system optimization models can be employed from community scale to city scale and even national scale. The time steps typically range from one hour to one month over a ten-year time horizon. In addition, high temporal granularity in long-term analysis usually leads to high computational complexity. To balance accuracy and complexity, various methods such as semi-dynamic methods, joint probability distribution methods, and stochastic programming were used.

In an energy system optimization model, a typical process is shown in figure 2. It mainly includes six parts:

1. Demand acquisition: selecting a suitable method for predicting the load curve of the IES.
2. Energy subsystem modeling: as shown in figure 1, the energy system compositions of IES usually includes renewable energy, energy production and conversion, energy storage, and energy network. In the planning and design of IES, energy system composition usually be modeled as a set of facility constraints with constant time steps in a certain analysis period.
3. Data simplification method: in large-span models, data simplification methods are used to reduce computational complexity without losing model precision.
4. Uncertainty analysis: in IES, the uncertainty mainly arises from the energy supply and demand. Uncertainty analysis is used to assess the robustness of the planning designs and options.

5. Scenario analysis: it refers to the process of analyzing possible future events by considering various possible results. In IES, this analysis is usually employed for building renovation, area reconstruction or climate change.
6. Multi-objective decision-making analysis: it provides decision-making strategy for different designs and assesses the design benefits for different fields like economy and environment.

2.2.1. Energy subsystem modeling

The typical components of energy system are shown in figure 1. The energy system can be divided into different subsystems including renewable energy, energy production and conversion, energy storage and energy network.

Renewable energy plays an important role in IES to reduce energy consumption and GHG emissions. Since renewable energy supply depends on the local environment, determining the potential and calculating the performance of renewable energy are significant in IES design and retrofit. In this review, solar, wind, and bioenergy are considered, since they are integrated more successfully in local areas reducing the grid transmission losses and grid congestion issues.

Solar technologies show huge development potential in urban energy systems. Especially in local areas, solar generation can be fixed on existing building structures without additional land. However, it is difficult to model solar radiation in urban areas, since complex shading patterns and various building heights, built densities, and roof slopes. In order to calculate the generation of solar energy in urban areas, urban solar availability and utilization factors should be taken into consideration [26]. On the other hand, to describe building design, grid digital elevation models and vector computer-aided design are usually adopted.

Wind energy could be adopted on both national and building scale. Building envelope wind turbines are considered as a component in micro-network. Liang *et al* [27] took wind speeds as important points in the urban wind turbines. However, with the micro-climate, the wind flows are difficult to predict. Computational fluid dynamics is the main modeling method.

Bioenergy is a potential environment friendly method for producing heat and power [28]. Combining the producing process, an integrated energy model with bioenergy is proposed by [29].

The use of renewable energy sources makes the energy system more environmentally friendly. Nonetheless, the energy supply depends on the prevailing local conditions, which leads to more uncertainty.

The heating network is an import component of an IES that connects distributed thermal energy devices. By means of storage devices, the heating network can separate the production and consumption of heat in time and space. In the framework of the International Energy Agency, the potential of integrated renewable energy and low temperature is presented to improve district energy efficiency. One of the drivers is the upgrading of buildings and the application of insulation technologies, which reduces the energy demand of new buildings [30]. This trend has led to a reduction in thermal demand density, while requiring accurate heat and pressure loss calculations. On the other hand, the development of IES creates opportunities for renewable energy sources and waste heat from cooling processes. With bidirectional, closed-circuit, and transient networks, renewable energy sources, waste heat and their storage can be integrated into a complex and efficient network. Fu *et al* [31] commented on the increased efficiency of a waste heat district heating network by a case study in China. In addition, the interaction of supply and cooling networks in tropical or temperate regions during the summer months is often included in the discussion of IES model [32]. In a word, through network of different energy components, energy flow could be transmitted over time and space, and diverse and complex energy system models could be founded.

Multi-energy systems involve processes for the production and conversion of different forms of energy, such as electricity, heating, and cooling. With the temporal and spatial mismatch between energy demand and renewable energy availability, multi-energy system planning is becoming increasingly important in IES system research. These processes can be achieved by adjusting the output between different devices or by energy storage. For example, combined heat and power (CHP), combined cooling, heating, and power (CCHP), heat pump (HP), electric chiller, absorption chiller, and fuel cell are used in interact between electricity, heating, cooling, and gas networks.

Energy storage is another method on solving the mismatch. During a high energy availability, excess energy is stored in the storage system to supply energy when insufficient. The battery storage is a common technique for wind power plants [33], while heat storage is a convenient solar storage method such as parabolic trough solar tower power plants [34]. Moreover, except battery and thermal storage, power-to-gas [35], and geothermal energy storage [36] are also promising technical routes in energy storage.

For power-to-gas, hydrogen is considered to be a promising energy carrier for storing energy [37]. However, with low volumetric density and high flammability, hydrogen storage is still a key challenge, and many researchers have tried to use ammonia as the chemical hydrogen storage. Through the reaction with nitrogen from the atmosphere, hydrogen which is produced by the hydrolysis of excess electricity is fixed in

Table 1. Temporal simplification methods.

Method	Description
Semi-dynamic balancing	Using typical days to decrease complexity and slice for historical periods
Balancing energy demand and renewable energy supply based on joint probability distributions	Fetching information from the joint probability of energy load and renewable energy generation
Stochastic programming	Determining the uncertainties for energy load and renewable generation

the form of ammonia, and Yuegu *et al* [38] explored this technique route in the solar photovoltaic (PV) power generation facility. Ganzho *et al* [39] investigated an ammonia-based energy storage system. With solid oxide fuel cell as energy conversion and steam turbine-based power generation cycle, the performance of this system design was evaluated. Chen *et al* [40] developed an ammonia-based thermochemical energy storage, and within synthesizer supercritical steam the heating was recovered by a heat recovery system.

For thermal energy storage, large ground- or water-based storage is usually utilized in district seasonal storage to bridge the temporal mismatch between heating demands in winter and solar availability in summer. There are four main underground thermal energy storage types: water tank, gravel water pits, boreholes, and aquifers [41]. Different researchers have reviewed these four types [42]. Borehole thermal exchanger could be connected to heating and cooling system to acquire the heat storage capacity.

Through combining energy integration, conversion, storage, and distribution, energy hub becomes an effective approach to manage energy flows from buildings to neighborhood and even national level [43]. With coupling the input and output of multi-energy, energy hub models were widely used in energy system optimization and evaluation.

For energy system optimization, mathematical programming techniques like MILP have been adopted to determine equipment capacity and operation [36]. One methodology of MILP model has been proposed in [44]. In this method, equipment quantity with certain capacity is regarded as integer variable, while discrete variables are used to describe operational status like on–off operation and power climbing. Plenty of research has been proposed. For example, Longxi *et al* [45] developed distributed energy network optimization model for selecting generation technologies in an area. Microgrid operation planning has been demonstrated with CHP [46] and renewable energy [47]. However, MILP is inadequate in certain plant performance [48]. To solve this problem, Yaran *et al* [49] adopted the MINLP model and compared with the origin of accuracy and computational time.

2.2.2. Data simplification

2.2.2.1. Temporal complexity simplification methods

The high temporal granularity model provides a more detailed operation scheme and more accurate solution, but with greater number of constraint equations, it is hard to solve. In order to reduce the solving difficulty without losing the energy demand and renewable energy availability information, many researchers have discussed various methods including semi-dynamic method, joint probability distribution method and stochastic programming.

In a semi-dynamic method, each typical day represents a portion of days in the year, for example, corresponding to some days in a season. Every day in turn could be decomposed into different time segments from several minutes to one hour. Due to chronology that could remain in every day, the value of storage systems and other sources could be determined during the year.

The second method is to balancing energy demand and renewable energy supply based on joint probability distributions. With this method, variability, and correlation of these two variables could be determined by a limited number of time slices. However, because of the lost chronology, the time series of these time slices cannot be founded, which limits energy storage calculation [50]. Nevertheless, based on the potential conversion between slices to achieve storage operation, Chong *et al* [51] explored the relation between intermittent power generation and power storage in the large-scale model.

The last method is stochastic programming. Using stochastic programming could resolve the model uncertainty. The application of stochastic programming depends on the scenario tree where each stage corresponds to a solution, and the scenario is characterized by a set of states from the stages. In this way, the measures for the cost of eliminating uncertainty could be provided with investments in back-up capacity and storage equipment. The temporal simplification methods are summarized in table 1.

2.2.2.2. Spatial architectural prototype model

In the neighborhood and city level, it is necessary to explore the interaction between buildings and the urban environment. For large-scale areas and even the entire city, prototype model for buildings is a feasible method [52]. The simplified model process includes cluster analysis, prototype development, and probability classification. Although most of the current research relies on prototype development from existing data and building information standards, the application of machine learning technology has opened new horizons in this field. This not only improves the accuracy of the model, but also speeds up the solution. In these methods, there are three main steps to build a prototype: (1) dividing the buildings into different groups according to their similar characteristics and energy requirements; (2) characterizing representative buildings; (3) calibrating model to reduce the difference between the predicted energy demand and the actual measurement.

By accessing the construction audit and construction inventory information, the actual value or average value of each parameter can be obtained and assigned to the corresponding prototype. This is a feasible way to build a prototype model [53]. However, since most of this data is limited in access, prototype building model development usually relies on statistics from building codes and standards, as well as previous research databases.

The uncertainty in building simulation includes specification uncertainty, modeling uncertainty, numerical uncertainty and scenario uncertainty [54]. Identifying and quantifying the uncertainty between the prototype model and the actual model is particularly important in prototype calibration. Among all the calibration techniques that can be used for building system models [55], the Bayesian calibration method has been proven effective in capturing the uncertainty of random parameters [56]. Peng *et al* [57] applied a virtual *in-situ* calibration based on Bayesian inference and Markov chain Monte Carlo to PV thermal HP system. In addition, Yixing *et al* [58] developed an auto-calibrated urban energy system model by learning the correlation between key model input parameters and building energy consumption from a reference building model, and analyzed a large office building in San Francisco.

2.2.3. Uncertainty analysis

As the analysis in section 3.2, the main uncertainty of IES planning and operation comes from the stochastic fluctuation of energy supply and demands. In order to quantify this uncertainty, researchers have adopted different methods. According to characteristics, variables of this stochastic fluctuation could be divided into continuous and discrete variables. Continuous variables include wind direction and solar radiation, while discrete variables include daily hourly demand.

For continuous variables, Monte Carlo sampling (MCS) is the most classic sampling method. Based on the genetic algorithm and MCS, Zhe *et al* [59] proposes a two-stage stochastic programming model for distributed energy systems. For the allocation problem of the renewable energy source, Xueqian *et al* [60] proposed a chance-constraint programming model based on the MCS method. This adaptive control strategy could find optimal PV-distributed grid allocation in distributed network. In order to improve sampling efficiency in MCS, Latin hypercube sampling (LHS) and Hammersley sequence sampling (HSS) could be used instead of simple random sampling. The LHS has been proved as a better method than simple random sampling in feasibility analysis for power systems including renewable energy [61]. On the other hand, the HSS method shows more success in improving the convergence of random annealing algorithm [62]. Furthermore, the relationship between different variables in the IES is essential. Copula function [63] and Nataf transformation [64] could be used to generate related samples.

For discrete random variables, scenario reduction methods like K-mean clustering are adopted to obtain typical scenarios and simplify calculations. For continuous variables such as wind direction and solar radiation, wind direction and PV scenario set generation are used to develop discrete random variables set from a large number of continuous variables. Jinghua *et al* [65] had analyzed the typical generating technology which can be used for power scheduling. And with Wasserstein distance metric optimum quantile method as scenario reduction method, Xueqian *et al* [66] had founded typical scenarios for an IES model containing power, heating, and gas.

2.2.4. Scenario analysis

Different from uncertainty analysis, scenario analysis is a process of analyzing the future possible environment. According to the various scenario results and their impact, decision makers could select the design for possible scenarios. These scenarios mainly include building renovation, area reconstruction and climate change.

Another research direction on scenario analysis is extreme and small possible events. There are three mainly types of extremes: transient events, disruptive drivers, and unexpected outcomes [67]. Transient events refer to events with low statistically possible, like sub-prime mortgages. Disruptive drivers might lead to mega-tends, like automation leading manufacturing jobs anticipated and economic alliances. Events happening out of expectation are regarded as unexpected outcomes, like the covid-19 global pandemic.

2.2.5. Multi-objective decision-making analysis

There are usually more than one optimization goals. In addition to the cost of energy supply, it is usually necessary to consider pollution emissions and the required system installation area [68]. A detailed summary of the solution algorithm for multi-objective optimization and suggestion for effectively obtaining the solution space are given [69]. Cui *et al* [70] discussed how to obtain an effective Pareto frontier in the energy-saving system to save energy, reduce emissions and costs. For the dispatch decision of the IES under multi-objective optimization, Li *et al* [71] combined multi-objective optimization with integrated decision making, and designed a two-stage method. The process of this two-stage multi-objective decision-making method includes: (1) finding non-dominated solutions through multi-objective optimization; (2) drawing the Pareto frontier according to the optimal solution; (3) using posteriori decision-making to select the optimal solution from all non-dominated solutions.

The algorithms used for multi-objective optimization can be divided into two categories: classic methods and meta-heuristic methods. In the existing ESOM literature, mainly classic methods include weighted sum, lexicographic, and eps-constraint method. On the other hand, meta-heuristic methods mainly include NSGA-II, MOPSO, and MOGA. When determining the final design through multi-objective decision-making, common methods include Shannon entropy, Euclidean distance, fuzzy theory, and evidential reason. Firstly, Shannon entropy methods quantify the uncertainty of information sources by introducing the concept of Shannon entropy [72]. The greater the Shannon entropy is, the greater the uncertainty is, and the smaller the weight of the objective in the decision-making process is. Secondly, based on the Euclidean distance method, the decision is made by measuring the distance between the candidate point and the ideal point [73]. Subsequently, fuzzy methods usually use fuzzy membership function to map each objective value between 0 and 1, and use different aggregation operators to determine the overall fuzzy fitness of each candidate point. The point with the highest overall fuzzy fitness is the most ideal point [74]. Finally, in the method based on incidental reason, the objective is defined as an optional solution attribute. Through the classification and evaluation of each attribute of the selected solution and the Dempster–Shafer belief combination, the objectives are integrated [75]. Jing *et al* [68] summarized and compared different multi-objective decision-making methods.

3. Typical tools and platforms

The development of IESs relies heavily on the support of simulation and planning tools and platforms. Finding suitable tools and platforms is of great significance for the design, investment, planning, and development of integrated energy projects. Currently, urban IESs and services are gradually being promoted nationwide. However, the related service modes and evaluation management are still in the exploratory development stage. Localized development and application of simulation and planning tools for IESs is a major hotspot issue [76]. Many domestic research institutions have carried out the research of IES planning and design software and platforms in China. The goals and backgrounds of these tools vary, and their applicability to specific problems and scenarios may differ. The transparency of various tools also varies. Some tools are openly available and can be reused, while others have limited transparency, with the source code not accessible. There are also tools that are restricted for internal use by specific organizations or personnel. Therefore, this section systematically summarizes the functional characteristics and applicability of typical simulation and planning tools for IESs in China.

3.1. DCOT

Designer's cogeneration optimization toolkit (DCOT) is an integrated design and calculation software developed by the Guangzhou Institute of Energy Conversion of the Chinese Academy of Sciences based on more than ten years of scientific research. It is aimed at energy-saving designers and uses general algebraic modeling system (GAMS) and designer's simulation toolkits (DeST) as its main tools. The software is programmed based on a database, which includes a comprehensive equipment and model library, regional energy price databases, and air conditioning load databases. In addition, it also has an algorithm library that includes LP, nonlinear programming, MILP, and MINLP. DCOT is mainly used in situations where energy optimization design (including power supply, heating, and cooling) is required. It can be applied not only to ordinary buildings but also to regional energy planning. Before using DCOT for energy planning, building simulation software such as DeST and design of experiments-2 (DOE-2) can be used to simulate building thermal environment design and obtain annual, daily, and hourly heating and cooling loads. Based on this data, the entire year can be divided into several operating conditions, which serve as the basis for the

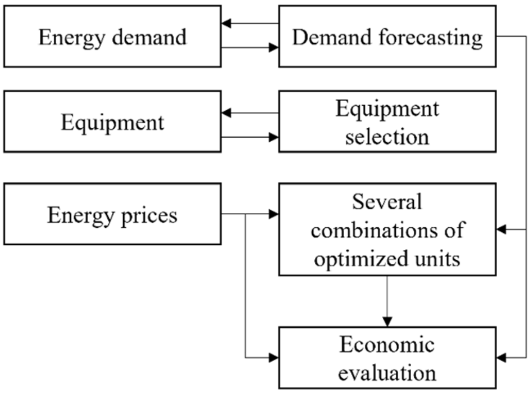

Figure 3. Development concept of DCOT.

Table 2. Application scenarios of microgrid in PDMG.

Status		Mode	
Grid connection	Normal	Load balancing mode	
		Smooth output mode	
		Scheduling mode	Peak shaving and valley filling System backup Scheduled generation
		Hybrid mode	Smoothing + peak shaving etc.
	Internal failure		
Isolated	Load balancing	No internal failure Internal failure	

optimization design in DCOT. After detailed building design plans for the community have been provided, load data for each operating condition throughout the year can be predicted, and energy planning optimization can be performed based on this prediction. The programming concept of DCOT software is shown in figure 3 [77].

3.2. PDMG

Planning and designing of microgrid (PDMG) is a practical software developed by Tianjin University based on its distribution network planning software platform. It has comprehensive microgrid planning and design functions, including intermittent data analysis, optimization of distributed power sources and energy storage capacity, energy storage system implementation design, and technical and economic comparisons combined with expert intervention. It has a dedicated inverter design module that calculates output voltage and energy consumption through modeling of different types of inverters, providing a basis for energy storage series–parallel design. In the intermittent data analysis function, PDMG has spectrum analysis and probability statistics functions, which can quantitatively reflect the intermittency and volatility of renewable energy from both the frequency and time domains. The application scenarios of PDMG software cover load balancing, smooth interconnection line power fluctuations, planned power generation, peak shaving and valley filling, as well as smooth peak shaving compound modes, as shown in table 2. The software adopts a process-oriented microgrid planning and design method, as shown in figure 4, which mainly includes data acquisition and analysis, distributed power source planning and design, energy storage system planning and design, and microgrid scheme evaluation [78].

3.3. DES-PSO

Distributed energy system planning design and optimization (DES-PSO) tool developed by Shanghai Electric claims to be the first planning and design software for distributed energy systems in China. Currently, it is applied to the planning and design of comprehensive energy systems. The software has ability to design, configure, invest, and analyze the system comprehensively, providing overall schemes for distributed energy systems. The design platform has a diverse range of data resources, providing strong support for solution design, including various energy technology models such as wind turbines, PVs, energy storage, and

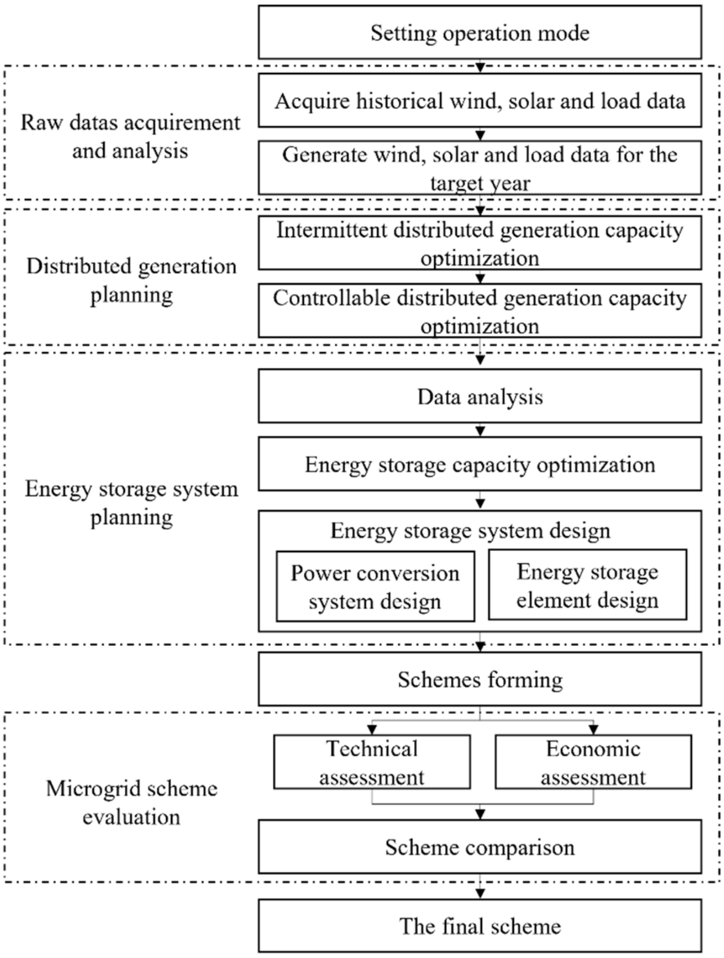

Figure 4. Flow chart of planning and designing of PDMG.

cogeneration, and comprehensive meteorological, equipment, and market data. The platform uses world-leading mathematical programming optimization tools and solvers to quickly solve complex energy system optimization problems with large-scale and long-term time spans. It is suitable for various distributed energy system design scenarios, and for typical systems, it adopts targeted optimization algorithms, which can reasonably determine the combination and scale of distributed energy system technologies. It is a comprehensive and highly integrated planning and design tool for distributed energy systems. The model in the software includes continuous and discrete variables, which effectively reflect the technical mechanism and operational characteristics of various models. Based on the powerful data analysis and processing capabilities of the industrial intelligent cloud platform, it provides rich meteorological, policy, market, and load-related data, making the calculation results more reliable. The software adopts a streamlined design approach, guiding users through standardized design, with the main process shown in figure 5 [79].

3.4. PIES

Planning for IES (PIES), developed by the Energy Internet Research Institute of State Grid Energy Research Institute, comprises five major functional modules: load forecasting, resource assessment, optimization planning, production simulation, and financial evaluation. It enables multiple energy demand predictions, local assessment of new energy resources, comprehensive energy system planning, system operation simulation, and project financial index calculation. PIES caters to the comprehensive energy planning needs of various scales and scenarios, such as single building/industrial enterprises, building clusters/industrial parks, and cities. The five functional modules can be run independently to support specific user requirements or jointly to provide one-stop systemized decision-making support services. The models in PIES consider the characteristics of various user types, technical and economic parameters of various elements, and external influencing factors such as energy prices, policies, and taxes. Furthermore, the software supports comparative analysis of multiple scenarios under different scenarios. The functional models of the comprehensive energy system planning software are illustrated in figure 6. It also includes four

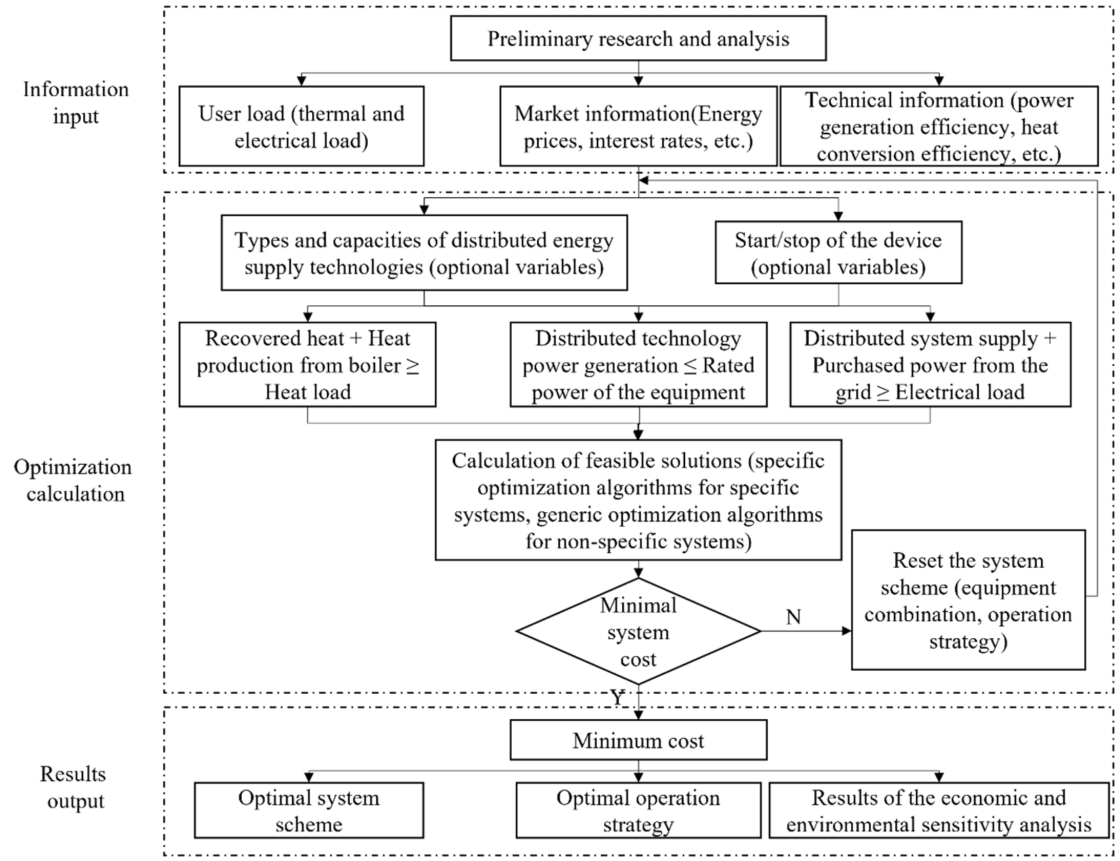

Figure 5. Flow chart for planning and design of DES-PSO.

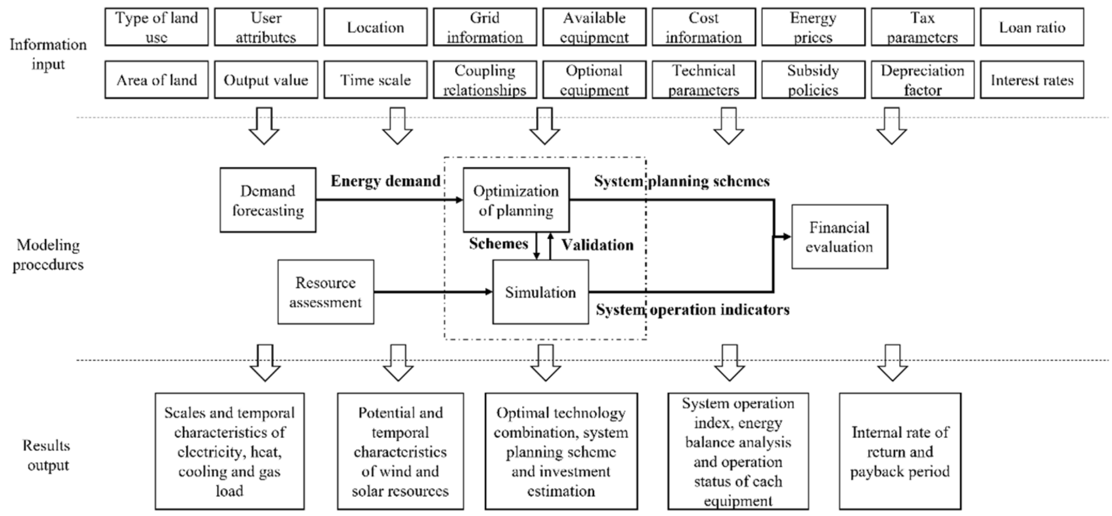

Figure 6. Functional illustration of the software model in PIES.

fundamental databases that cover a range of useful services for the user: a full-year 8760 h wind and solar resource database covering kilometer-level spatial granularity, a user load database that characterizes different zones, users, and scenarios, an energy equipment database covering approximately 500 major brands in the market, and an energy price database covering various provinces and regions. Moreover, it provides a limitless full linkage automatic combination of '15 + 3' types of energy facilities, comprising 15 types of energy conversion equipment and three types of energy networks. The back-end generates a combination plan to ensure that the optimal solution is found. In terms of interaction and operation modes, and report generation, the software also includes some user-friendly functions, such as automatic report export and graphical or report form presentation to assist users in planning [80].

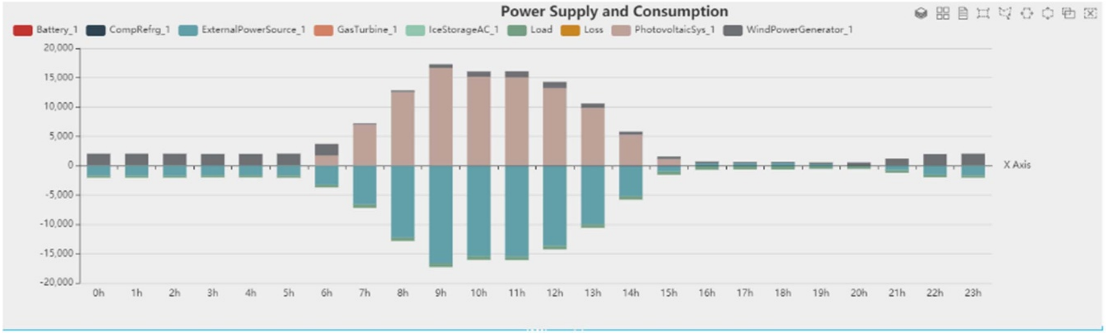

Figure 7. Example of simulation results for a power grid in CloudPSS-IESLab.

3.5. CloudPSS-IESLab

The CloudPSS platform is a digital twin application development platform for the energy internet developed by Tsinghua University. It utilizes a completely self-developed electromagnetic transient simulation kernel and cloud-based heterogeneous parallel computing resources to provide users with modeling, simulation, and analysis functions for various energy networks, including AC/DC hybrid power grids, renewable energy generation, microgrids, distribution networks, and heating networks. The IESLab module is a cloud platform for comprehensive energy system planning and design that focuses on multi-energy systems coupled with electric power, heat energy, solar energy, wind energy, batteries, and energy storage. Through modeling and simulation technology, it analyzes system operation characteristics. It consists of data management and modeling and simulation modules. The data management module allows for the input and management of various types of basic data, while the modeling and simulation module is used for the construction of system topology and the display of simulation results. The platform supports the modeling and simulation calculation of multi-energy system coupled networks, including distribution systems, heating and cooling systems, steam heating systems, and flue gas waste heat recovery systems. Unlike traditional comprehensive energy system simulation tools, the platform integrates more than 20 common comprehensive energy system equipment models, allowing users to flexibly build comprehensive energy systems with any form of energy cascade utilization and unconstrained topology. It also supports simulation calculations for grid-connected and isolated systems, as shown in figure 7. The main application scenarios of CloudPSS-IESLab include comprehensive power grid systems composed of various energy forms such as traditional energy generation, new energy (centralized/distributed wind and solar), and energy storage; comprehensive thermal systems composed of cogeneration, thermal boilers, and refrigeration and heating; and comprehensive gas networks composed of natural gas pipelines, gas turbines, and gas storage and supply. It aims to assist users in modeling and simulation, energy management, and operational optimization of comprehensive energy systems, as well as in equipment selection and configuration, operational optimization, and comprehensive benefit evaluation [81].

3.6. IES-Plan

IES-Plan is a comprehensive energy system planning software developed by Southeast University, capable of supporting the planning of four types of energy: electricity, heating, cooling, and gas. It includes a complete database of diversified energy equipment, such as CHP units, gas boilers, fuel cells, wind turbines, and other key devices, and supports parallel planning and comparison of multiple IESs [82]. The software first models the load and analyzes the operating mode of the load for the corresponding application scenario through the load analysis module, simulating the electric, cooling, and heating loads of the application scenario. Then, the available natural resources in the area are analyzed and simulated through the resource endowment evaluation module to assess the local self-sufficiency capacity of energy. The energy infrastructure, resource endowment, and energy load are then input into the model, and a series of solutions are generated based on energy balance. Furthermore, it compares and analyzes the solutions from multiple dimensions, such as economic, environmental, and energy efficiency, to ultimately achieve optimal planning. It provides several key features, such as multiple load modeling methods based on core equipment, subdivision of industry and business type, support for user-defined multi-planning scheme comparison, and customizable modeling of 28 parameters for the core equipment of the IES. The software also includes natural resource endowment data from over 700 meteorological stations nationwide, considers parameters such as energy purchase and sale prices, financial parameters, and new energy subsidies, and provides visual analysis and comparison of planning solutions, as well as an automatically generated report. To ensure the optimization and speed of

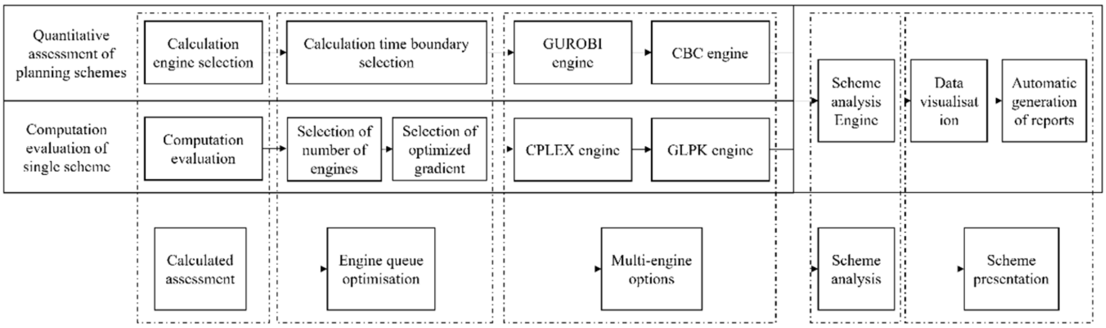

Figure 8. Optimization flowchart of computation engine in IES-plan.

multi-planning solutions, IES-Plan has an engine queue optimization function that accelerates the solution process. During the multi-solution process, the background first evaluates the number and amount of calculation of the selected initial solutions and selects the engine and the number of threads for computing. After the calculation is completed, the data is reorganized and transmitted to the front-end visualization interface, as shown in figure 8 [83].

3.7. iEnergyLab

iEnergyLab is a comprehensive energy twin software developed by Shanghai KeLiang Information Technology Co., Ltd, based on multidisciplinary, multi-physical system coupling and multi-time scale modeling and simulation. It integrates multiple operational data sources to construct a precise mirror image of physical systems, providing a virtual object and operating environment for researching comprehensive energy systems. This powerful tool is designed for comprehensive energy system planning, design and evaluation, energy management and dispatching, real-time control and optimization, carbon emission calculation and assessment, intelligent diagnosis, and operation and maintenance. It supports multi-scenario construction and multi-project management, utilizing the iEnergyModel library of verified comprehensive energy system simulation models to achieve fast and dynamic simulation at the device, unit, and system levels. The electric power system simulation model supports modeling of PV, wind turbine, hydraulic power generation, diesel power generation, battery storage, supercapacitor storage, transformers, reactive power compensation, lines, loads, and more. The thermal system modeling and simulation use the Thermolib thermodynamic simulation tool to model air conditioning, HPs/chillers, gas boilers, refrigerators, fuel cells, and heat exchangers. The software uses multi-core and multi-rate calculation to balance model accuracy and computation speed and solve the decoupling problem of different types of energy in multiple time scales, ensuring smooth and efficient simulation of comprehensive energy systems. The software workflow is illustrated in figure 9 [84].

3.8. Integrated energy planning, design, and simulation analysis tool

The integrated energy planning, design, and simulation analysis tool, developed by XJ Group Co., Ltd, is a system software designed for the pre-planning and evaluation of comprehensive energy projects. It comprises multiple functional modules, including energy resource analysis, heating and cooling load analysis, energy system construction and equipment selection, energy system operation optimization, economic evaluation analysis, and planning reports. The software's logical flow is illustrated in figure 10 [85]. It can conduct resource analysis and supply–demand forecasting based on local energy resources, such as wind, solar, temperature, and geothermal energy. It utilizes supply–demand balance and multi-objective optimization algorithms to achieve the macro-selection of distributed energy stations, such as distributed PVs, decentralized wind power, and ground source HPs. The software also supports equipment selection and sizing for multi-energy supply systems and energy storage systems, and generates comprehensive energy supply technology routes and design schemes for various typical energy usage scenarios, such as schools, hospitals, enterprises, commercial complexes, and parks. It meets the requirements of project feasibility analysis and preliminary planning and design.

3.9. Tian Shu Yi Hao platform

Tian Shu Yi Hao platform is the core of the comprehensive intelligent energy industry of State Power Investment Corporation. It integrates intelligent energy monitoring, prediction, regulation, analysis, and services, and is widely applicable to various energy application scenarios such as residential, commercial,

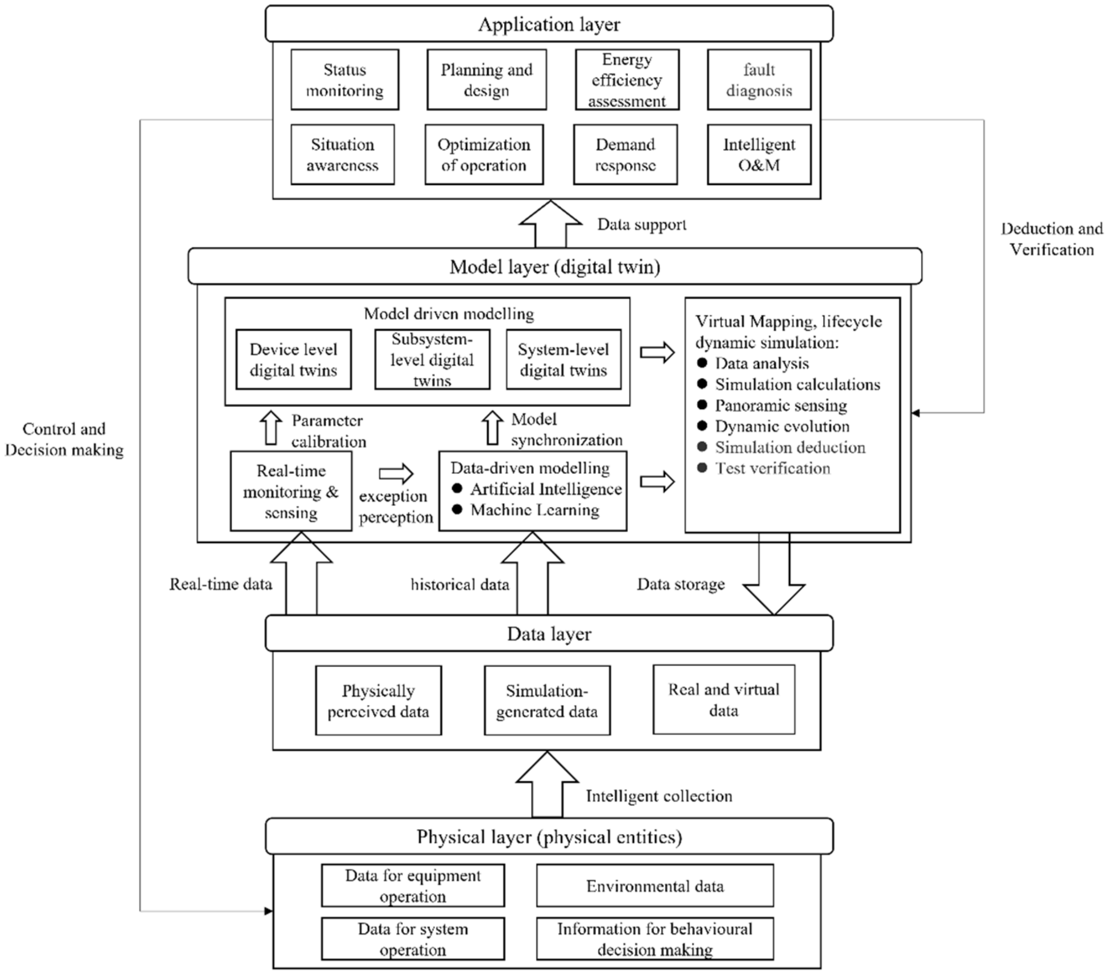

Figure 9. Flow chart for iEnergyLab.

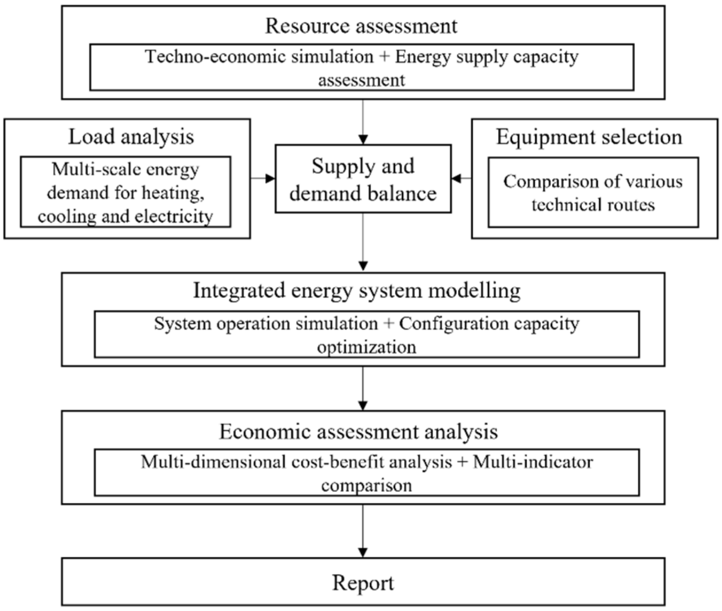

Figure 10. Logic flow chart of the software.

industrial, and park. Developed by State Nuclear Power Engineering Co., Ltd, the platform includes nine major functions, 49 applications, and more than 300 intelligent algorithms. Based on cloud, big data, internet of things (IoT), mobile, intelligent, and blockchain technologies, it can achieve comprehensive control of dozens of different types of energy. The platform follows a system integration concept of 'horizontal cross-border integration, vertical business connectivity', integrating multiple categories of energy systems to support data sharing, secure communication, interoperability, scenario linkage, flexible participation, and unmanned operation, providing a unified solution for managing comprehensive intelligent energy in multiple regions and scenarios. Its intelligent prediction module provides practical operation guidance for operators to make the most of peak-valley electricity prices and energy storage devices. Its intelligent regulation module can balance the energy supply structure in the region to maximize the economic impact of comprehensive intelligent energy projects based on external factors such as grid peak-valley electricity price difference. So far, Tian Shu Yi Hao platform has been deployed in comprehensive intelligent energy projects in Xiaogang Village in Anhui, Jinggang mountain and Yan'an Cadre Academy [86].

3.10. The IES simulation platform

The IES simulation platform developed by North China Electric Power University consists of four major modules. The first is the planning and optimization module, which achieves optimized selection of top-level design plans and provides design support for the design department of specific projects. The second is the operation and optimization module, which builds a control platform and optimizes the output of various types of energy on a daily, hourly, and time-period basis. The third is the market trading module, which mainly realizes the trading of various energy types in distributed and micro-grid forms. The fourth is the benefit evaluation module, which includes comprehensive evaluations of economic, environmental, and social benefits. The planning and optimization module among the four modules serves project design, while the other three functional modules are operation and maintenance platforms after project investment. Currently, the vast majority of integrated energy service management platforms in the market are operation and maintenance tools, while North China Electric Power University combines front-end planning and design with back-end operation and maintenance functions [82].

3.11. Integrated energy planning and simulation software

The East China Electric Power Design Institute has independently developed an integrated energy planning and simulation software that includes five major functional modules: rapid planning of IESs, phased construction planning of IESs, zoning planning of IESs, evaluation of operation modes, and optimization of operation modes. It is available in both PC and mobile versions, supporting browsing on various devices such as computers, tablets, and smartphones. The phased module supports up to three stages of construction and plans with corresponding load demands to reduce initial equipment redundancy while meeting the increasing load demands of the park's development. The zoning module supports simulation of up to four areas and selects energy demand types and connection relationships for each area, matching and filling in the load information of each area. The results page displays the equipment configuration of each area separately. The optimized simulation goals of the low-carbon energy system planning software include optimal economy, energy efficiency, and environmental emission reduction, with the ability to adjust the weight coefficients of various emissions. Users can fill in actual parameters and add operational, financial, and environmental parameters accordingly. The energy pricing function built into the low-carbon energy system planning software allows for the resetting of the output prices of different energy forms by clicking the back-calculation button and setting different internal rates of return for completed planning analyses. The software can output the on/off status and energy flow direction of equipment at different times and also display the system energy flow situation more intuitively by playing the topological relationships between different equipment at various times through a system energy flow chart [87].

3.12. CEPAS

CEPAS is an IES modeling toolkit developed by Xiamen University. It consists of a series of models for optimizing and evaluating urban energy systems, including energy demand forecasting models based on agent energy consumption behavior, regional grid optimization models, system optimization models, multi-objective decision-making methods, multi-index evaluation strategies, and multi-agent benefit distribution model. The energy demand forecasting model is an agent-based model, and the energy consumption behavior model is based on the Markov chain approach. The energy system optimization model is based on the MILP and MINLP methods, and is highly flexible. It can optimize the energy system from the user level to the city level, and can optimize from the entire life cycle of the equipment to the hourly operation of the system. The multi-objective decision-making models are used in multi-objective situations to decide the best planning scheme from multiple optimal planning schemes to support actual project construction [68]. The multi-objective decision method is an evaluation system for IES design options that combines the modeling generation alternative method and the eps constraint method. It can be used to evaluate the impact of various subsystems in an IES, such as CHP and PV, on the overall economic and environmental benefits [88]. The strength of this software package is that it combines a holistic approach to demand forecasting, system optimization and scenario evaluation. It allows to evaluate the energy system as a whole and to assess the impact of energy technologies in the system.

In summary, a brief description of these tools is shown in table 3.

4. Integrated energy service in China

Integrated energy service is oriented to the end of the energy system, oriented to the needs of users, and through the combination of energy varieties or system integration, energy technology or business model innovation, etc., to enhance the benefits or satisfaction of users. In China, as an advanced form of energy service, integrated energy service aims to provide energy solutions that conform to the direction of energy development and meet the actual needs of customers, and is an important initiative to promote the energy revolution. At the same time, integrated energy services can effectively improve energy efficiency and promote clean energy use, and vigorously developing integrated energy services will be a key focus point for promoting China's low-carbon energy development and achieving the goal of carbon peaking by 2030 and the vision of carbon neutrality by 2060 [89].

As a new form of energy service, the integrated energy service market has huge potential, many participants, diverse business models, and a long industrial chain with distinctive characteristics [90]. A typical schematic diagram of the integrated energy service business model in China is shown in figure 11. From the view of energy layer, for different user needs, the IES investor makes an investment and operation planning of the proposed IES through modeling, and the IES is operated by the IES operator to meet the energy needs of users in terms of cooling, heating, electricity, and gas. The gas and insufficient electricity are purchased from the gas company and the power company, and the excess electricity is sold. In most cases, the IES investor and operator are one and the same, collectively referred to as the integrated energy service provider. The integrated energy service provider is both the dispatch center and the operator of the IES. At the information level, the integrated energy service provider collects energy consumption data from customers and various energy costs data in the energy market through the energy aggregators, analyzes and processes them, then bargains and contracts with customers, sells energy to them to obtain energy sales revenue and bears the energy production costs. In addition, integrated energy service providers can improve their own economic efficiency and promote the surplus power consumption of the system through a scheduling strategy based on integrated demand response (DR) [91].

Therefore, integrated energy services in China can be divided into three main categories: investment and operation planning, DR, and energy trading and pricing. The following is a review of relevant research.

4.1. Investment and operation planning

The investment and operation planning of IES is closely related to its case scenarios [92]. In China, there are various case scenarios, which are divided into three categories: energy base type represented by PV power plants, wind power plants, nuclear power plants, etc., cluster building type represented by hospitals, office buildings, commercial buildings, etc., and industrial park type represented by industrial zones, island, and ports, as shown in figure 12. Integrated energy service providers have different focuses when planning the investment and operation of IESs for different types of case scenarios, and the challenges that need to be solved based on ensuring energy supply are also different.

4.1.1. Energy base type

For energy base type case scenarios, the randomness and volatility of wind and solar power may lead to problems such as spatial and temporal imbalance between the supply side and the demand side, while abandoned wind, abandoned solar, surplus nuclear power and other excess power generation will lead to low unit utilization hours, low energy utilization efficiency [93]. For such case scenarios, some current studies are considering combining energy storage, hydrogen energy, heat storage and heat supply to create an overall solution for energy bases with functions of multi-energy complementarity, peak shaving and valley filling, circular economy, and diversified development. Ming *et al* [94] discussed the possibility of complementary operation of PV and hydropower in China by optimizing the scale of integration of utility-scale PV plants with hydropower plants through cost–benefit analysis and consideration of downstream water level changes. An integrated CHP system consisting of a CHP unit, a wind power plant and a condensing power plant was studied to explore its ability to improve the utilization of wind power by incorporating electrical energy storage and thermal energy storage to improve the flexibility of the system on both the heat and power

Table 3. The key features of all the tools/platforms.

Tool/platform	Applicable scenarios	Type of load	Optimization objectives	Outputs	Transparency
DCOT	Power, heating, and cooling supply	Cold, heat and electricity	Minimal energy consumption	Combination of units, economic evaluation	Source code inaccessible, reusable and not publicly available
PDMG	Microgrid	Electricity	Optimal combination of economy and technology	Microgrid system design schemes	Source code inaccessible, reusable and not publicly available
DES-PSO	Off-grid microgrids, power, heating, and cooling supply	Cold, heat and electricity	Optimal economy, minimal CO_2 emissions	Optimal system configuration options, economic parameters, sensitivity analysis	Source code inaccessible, reusable and **publicly available**
PIES	Integrated energy system	Cold, heat, electricity, gas, and water	Optimal economy, optimal technology, minimal CO_2 emissions	Load forecast, renewable energy assessment, optimal system configuration options, economic evaluation, system operation analysis	Source code inaccessible, reusable and not publicly available
CloudPSS-IESLab	AC/DC hybrid power grids, renewable energy generation, microgrids, distribution networks, and heating networks	Cold, heat, and electricity	Optimal economy, optimal technology	System operation analysis, comprehensive benefits evaluation	Source code inaccessible, reusable and **publicly available**
IES-Plan	Integrated energy system	Cold, heat, electricity, and gas	Optimal economy, optimal technology, minimal CO_2 emissions	Load forecast, renewable energy assessment, optimal system configuration options, economic evaluation	Source code inaccessible, reusable and **publicly available**
iEnergyLab	Power, heating, and cooling supply	Cold, heat, and electricity	Optimal economy, optimal technology, minimal CO_2 emissions	Status monitoring, optimal system configuration options, fault diagnosis, energy efficiency assessment, economic evaluation	Source code inaccessible, reusable and not publicly available
Integrated energy planning, design, and simulation analysis tool	Power, heating, and cooling supply	Cold, heat, and electricity	Optimal economy	Optimal system configuration options, equipment selection, economic evaluation	Source code inaccessible, reusable and not publicly available
Tian Shu Yi Hao platform	Integrated energy system	Cold, heat, electricity, gas, and water	Optimal economy, optimal technology, minimal CO_2 emissions	Renewable energy assessment, optimal system configuration options, economic evaluation, system operation analysis	Source code inaccessible, reusable and not publicly available

(Continued.)

Table 3. (Continued.)

Tool/platform	Applicable scenarios	Type of load	Optimization objectives	Outputs	Transparency
The integrated energy system simulation platform	Microgrid	Electricity	Optimal economy	Microgrid system design schemes, comprehensive benefits evaluation	Source code inaccessible, reusable and not publicly available
Integrated energy planning and simulation software	Power, heating, and cooling supply	Cold, heat, and electricity	Optimal economy, optimal technology, minimal CO_2 emissions	Optimal system configuration options, economic evaluation, system operation analysis	Source code inaccessible, reusable and not publicly available
CEPAS	Integrated energy system	Cold, heat, electricity, and gas	Optimal economy, optimal technology, minimal CO_2 emissions	Load forecast, renewable energy assessment, optimal system configuration options, economic evaluation	Source code inaccessible, reusable and not publicly available

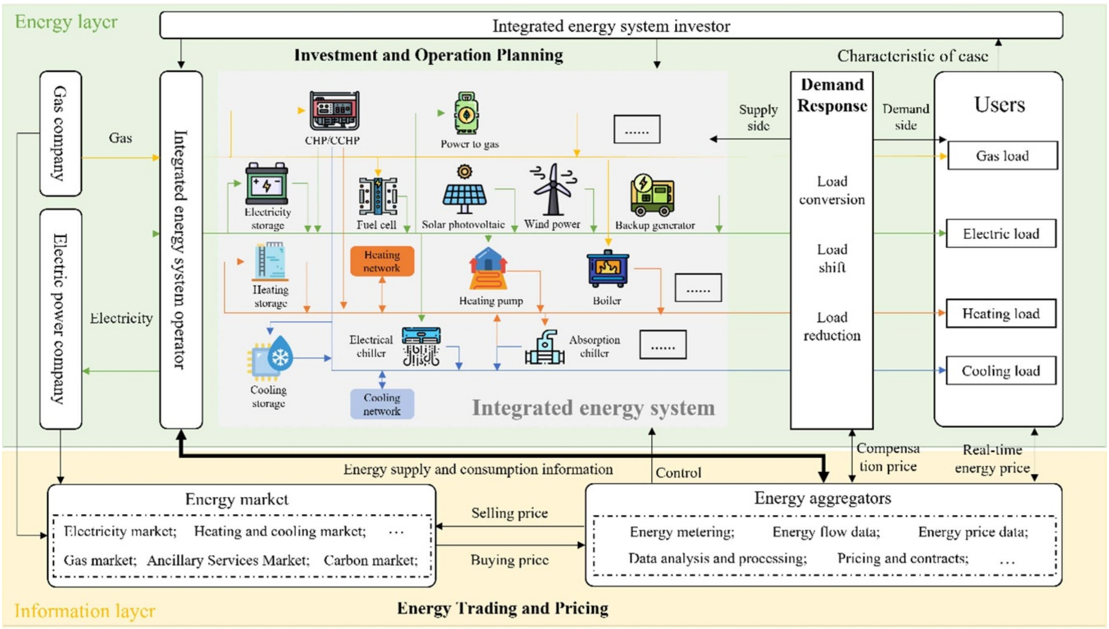

Figure 11. A typical schematic diagram of the integrated energy service business mode in China.

supply sides [95]. Gong and Gong *et al* [96] developed a model considering the joint operation of nuclear and pumped storage power plants for the operational characteristics of nuclear and pumped storage power plants, and evaluated the benefits of both plants for peaking.

4.1.2. Building cluster type

In a building cluster type case scenario, the energy demand of users is inseparable from the building function. For a building cluster, the energy demand of users of different functions of the building varies greatly [97]. Furthermore, for this type of case scenario, using traditional energy supply methods consumes more energy and generates a lot of pollution. Therefore, more and more researches focus on how to make full use of local clean energy resources and design suitable IESs to meet the complex energy demand of users and promote regional low-carbon development. Li and Zhao [98] proposed an IES planning model including gas turbines, wind turbines, solar PV panels, ground source HPs, absorption cooling/heaters, batteries and thermal storage for Harbin City Hospital, and chose primary energy savings rate, annual cost savings rate and CO_2 reduction rate as the objectives for multi-objective optimization. The IES planning of commercial buildings in Xi'an, Guangzhou and Harbin was modeling, and a comprehensive evaluation method was used

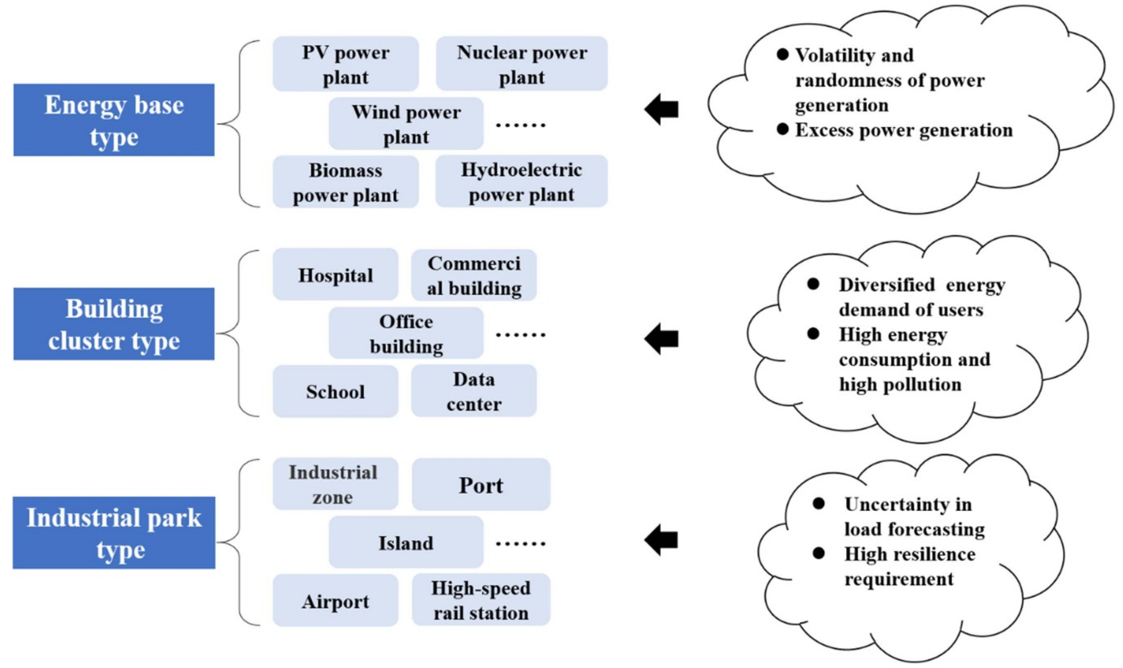

Figure 12. Case scenario classification and challenges of integrated energy services.

to assess and compare the performance of IESs in three different regions in terms of economic, environmental and efficiency benefits [99]. Si *et al* [100] developed an optimization model of an integrated solar energy system for an office building in Lhasa to evaluate its energy efficiency and economic benefits, which aimed to explore the issue of optimal utilization and economic benefits of solar energy resources for buildings in Chinese cold regions of the plateau. For school buildings in Hong Kong, an integrated energy service scheme was designed with the goal of zero energy consumption, i.e., high performance building envelope, energy efficient air conditioning system and lighting equipment to save energy, and rooftop PV equipment with building integrated PV panels to meet energy demand [101]. For data centers, an integrated planning scheme that optimally determines the locations and capacities of interconnected internet data centers and battery energy storage systems in a smart grid was presented. The model is formulated as a multi-objective optimization problem, in which both computational performance metrics of internet data centers and operational criteria of the grid are coordinately considered as three inter-related but conflict objectives, the coupling impact between the cyber and energy resources are modeled [102].

4.1.3. Industrial park type

The energy demand of industrial park type case scenario is closely related to the industrial structure in the park, therefore the load prediction is difficult when modeling the IES planning problem. Moreover, for industrial park type scenario users, a sufficiently high supply reliability or energy system resilience is required, and a sudden supply interruption accident may generate a large economic loss [103]. Most of the current research focuses on building an overall IES solution for industrial parks with high energy reliability, graded utilization, and circular economy to meet the different types of energy demand of parks such as transportation, logistics, industry, and construction. Chen *et al* [104] studied the energy demand and load characteristics of various buildings in an IES dominated by industrial parks in China. In addition, the characteristics of different energy forms are analyzed in detail. The analysis results of this paper can lay the foundation for the design and operation planning research of IESs in complex industrial parks. For industrial zones, Yan *et al* [105] developed a two-stage optimization approach to plan an IES with multiple flexibility options including gas boilers, electric boilers, power-to-gas, electric energy storage and thermal energy storage with the objective of minimizing the total cost including equipment investment, operation, carbon emission penalties and renewable energy reduction penalties, and analyzed the economic performance and renewable energy accommodation of the system. With the goal of building a green port, Song *et al* [106] proposed a zero-carbon port microgrid energy system with an integrated carbon capture power plant and developed an energy management model considering carbon trading mechanism to achieve optimal economic operation of the port microgrid and reduce carbon emissions. Li *et al* [107] presented a planning model for a 100% renewable island energy system that combines electricity to gas, CCHP, and desalination technologies to provide electricity, heating, cooling, gas, and fresh water to local residents. Xiang *et al* [108] developed an MILP optimization method for sizing the capacity of hydrogen energy systems, PV, and battery storage in an electrified airport IES with the optimization objective of minimizing the total economic cost and considering the environmental benefits of a proposed airport microgrid system.

4.2. DR

DR is based on the price or incentive information of various energy sources such as natural gas, electricity, heat, etc., to guide users to actively change energy consumption behaviors, optimize energy use methods, transfer, and reduce energy load for a certain period of time, and convert energy use through energy coupling equipment types, so as to achieve an optimal balance between energy supply and demand [109, 110]. As shown in figure 11, the users can change their energy use mode by reducing the energy load (load reduction), shifting the energy use period (load shift), or converting the type of energy use (load conversion). According to different economic regulation models, DR can be divided into price-based DR (PBDR) and incentive-based DR (IBDR) in China. Both mechanisms can promote the motivation and activity of users to participate in DR [111].

4.2.1. PBDR

In PBDR, the integrated energy service provider uses time-of-use pricing to raise energy prices during peak periods and lower them during low periods. Through direct price regulation, different types of users, such as residential, commercial, and industrial, regulate their energy consumption based on energy demand and energy prices. PBDR pricing methods include real time pricing (RTP), critical peak pricing (CPP), time of use plus CPP (TOU-CPP), and variable peak pricing [112]. Many studies have been conducted in China to design and model PBDR analysis. For example, Tang *et al* [113] developed a Stackelberg game-based interaction strategy between utilities and multiple smart buildings to reduce costs and increase grid revenues due to load fluctuations. However, since this approach is only for the scenario where the energy supply is monopolized by one utility, the applicability of the approach is not strong. Yu and Hong [114] proposed a price-based real-time DR algorithm that obtains data from an hourly simulated electricity trading process to achieve optimal load control for different devices. Chai *et al* [115] developed a two-tier model to extend PBDR to retail electricity markets where multiple retailers compete. To cope with the uncertainty of campus-level IESs and to reduce carbon emissions, Lyu *et al* [116] proposed a low-carbon robust economic dispatch model that considers price-based integrated thermoelectric DR and vehicle-to-grid. Wu *et al* [117] developed an improved optimization model for the DR of a local off-grid microgrid on the Dongfushan Island, China, to develop energy dispatch and economics considering different tariffs under different seasonal meteorological conditions. Currently in China, CPP and TOU-CPP are primarily being piloted in some industrial parks. RTP and variable peak pricing are still in the research stage.

4.2.2. IBDR

IBDR means that the integrated energy service provider (energy retailers or utilities) encourages users to participate in peak load reduction in the energy system based on a signed agreement. Under this mechanism, users who reduce their energy use during peak hours are compensated financially. IBDR can be an effective aid to ensure the security and stability of energy supply in emergency situations of supply constraint or equipment failure [118], and there are two main types of incentive models: direct load control (DLC) and critical peak rebate (CPR). DLC refers to the load aggregator or electric company directly controlling the load of users, while CPR refers to the users receiving a direct subsidy by reducing the peak load actively. The focus of the above models is on the dispatching strategies of both supply and demand. Among them, Chai *et al* [115] determine the optimal incentive subsidy based on the acceptance level of user participation in response from the perspective of user response behavior. Ding *et al* [119] designed an incentive mechanism for DR with considering the coupling between multiple energy conversion efficiencies and energy quality depreciation in the energy stepping process, the case study showed that the designed incentive mechanism could further reduce users' energy purchase costs. Wen *et al* [120] proposed a deep learning model based on recurrent neural networks to predict the wholesale electricity price, PV generation and electricity load for the following day, and used reinforcement learning to find the optimal incentive price, which was then demonstrated in a case study to reduce peak demand. In fact, DLC and CPR have pilot projects in some cities in China, which do not currently have the necessary conditions for widespread implementation.

4.3. Energy trading and pricing

Currently, most research on energy trading and pricing in integrated energy services is focused on the community level [121]. In an energy community in China, as shown in figure 11, when an integrated energy service provider conducts an energy trading with a user, both parties' bargain through the energy aggregator based on information such as energy demand and energy cost. In addition, a PBDR strategy or an IBDR strategy may help users to adjust their energy demand appropriately, thus reducing the total energy cost of the system and helping integrated energy service providers and customers to reach a win–win situation [122]. In fact, multiple integrated energy suppliers can also participate in energy markets such as electricity market and ancillary service market with utilities such as electric power companies and gas companies.

4.3.1. Trading with energy users

In an energy community, an integrated energy service provider can coordinate the distribution of energy within the region and enable distributed energy supply coordination at the user level through an energy aggregator [123]. Through energy aggregators, sometimes community users can act as generators and consumers to reduce their own costs and the operating costs of the whole community through trading [124]. A series of exploratory studies have been conducted by related scholars on energy trading and pricing in integrated energy services within energy communities. Zhang *et al* [125] presented a user-driven electricity market for an integrated microgrid energy system and discusses possible pricing strategy options and analyzes the potential destabilizing effects of collective user trading behavior. Luo *et al* [126] took electric power and natural gas utilities as the top energy supplier and energy systems equipped with micro turbines and boilers as energy suppliers to provide users with flexible power and heat supply. In this system, the energy supply distribution among different energy subsystems was calculated through non-cooperative game, and the revenue distribution among energy suppliers, aggregators and users was realized through cooperative competition. Wang *et al* [127] presented a distributed and coordinated trading mechanism for an integrated community energy system using a three-level game model. The vertical trading aspect is formulated as a dual Stackelberg game, in which a load aggregator acts as an intermediary between energy centers and residential customers. The horizontal bidding between energy centers is modeled as a non-cooperative game in which each stakeholder pursues the best interest.

4.3.2. Trading with utilities

When multiple integrated energy service providers participate in energy market transactions together with utilities companies, it means that energy can flow freely from one IES to another [128]. The networked IESs is proposed to realize the interconnection and interworking [129]. For utilities companies, there is an eternal conflict between high energy demand and limited energy supply, therefore, interactive transactions between multiple integrated energy service providers and utilities can help to eliminate this conflict [130]. Some researches begin to explore the trading mechanisms and pricing strategies for multiple integrated energy service providers with utilities companies. Xia *et al* [131] first identified the functions of distributed energy storage in wholesale and transactional markets, and then provided detailed mathematical models of distributed energy storage in various transactional market types, which focused on the pricing mechanism for the contribution of distributed energy storage in peer to peer (P2P) transactional energy markets. With the large-scale application of microgrids in distribution networks, Sun *et al* [132] developed a coalition game-theoretic energy trading algorithm for networked microgrids that can effectively improve the efficiency of energy trading and coordinate the energy trading that occurs between microgrids and between microgrids and grids to reduce the operational burden they impose on the power system.

A virtual power plant (VPP) is a typical example. Integrated energy service providers can combine clean energy, controllable loads, and energy storage systems through a distributed energy management system, and participate in grid operations as a special power plant. This helps to coordinate the conflict between smart grids and distributed energy resources, and fully exploit the value and benefits that IESs bring to the grid and users. The VPP provides a new way for integrated energy service providers to expand the use of distributed energy and controllable load resources [133]. The profit source of the VPP service model comes from the purchase and sale price difference. As a resource collection entity, the VPP can participate in market competition as the main body of power sales and obtain more profits. In this mode, integrated energy service providers who join the electric power sharing pool can easily conduct power transactions and maximize the use of distributed renewable energy from their respective distributed energy storage devices, reducing the purchase of power and greatly lowering power costs with end-users. In terms of VPP scheduling, Wei *et al* [134] incorporated distributed energy resources and controllable loads into the optimal dispatch of power sales companies, establishing an optimal dispatch model for maximizing the daily operating income of power sales companies. Tao *et al* [135] developed a two-layer optimal scheduling model for the distribution network-VPP, considering the characteristics of the fixed VPP resource combination participating in the operation system of the power sales company in the fixed node model. Qin [136] studied the optimal scheduling and market bidding strategy of the VPP from three aspects: the VPP's strategy for participating in market bidding, the intra-day optimal dispatch of the VPP, and the VPP's participation in power market bidding. Finally, Xuanyuan *et al* [137] constructed a 'wholesale-retail' two-level market trading system for the VPP and measured the economic efficiency of the VPP service model.

5. Exemplary project

The demonstration project of IES is the pioneer in verifying and showcasing the technology and achievements of IES, which is of great significance for the research and innovative application of corresponding business models. Currently, China has successively issued a series of national policies and regulations, such as the Guidance on Promoting the Integrated Development of Power Generation, Transmission, Distribution and Storage and the Comprehensive Utilization of Multiple Energies by the National Development and Reform Commission (NDRC) and the National Energy Administration (NEA) (NDRC NEA Doc. [2021] No. 280) and the Notice on Printing and Issuing the '14th Five-Year Plan' for the Modern Energy System by the NDRC and NEA (NDRC NEA Doc. [2022] No. 210), to promote the construction and development of IESs [138]. In addition, relevant research institutions have been increasing funding for the research field of IESs. Taking the energy internet, which is closely related to IESs, as an example, the National Natural Science Foundation of China has funded about 804 projects in the field of energy internet from 2011 to 2020 [139]. With the encouragement and guidance of various policies and regulations and the strong funding support from research institutions, many universities, research institutions, and companies at home and abroad have invested in the research and development, as well as practical application of IESs, and successively built several demonstration projects of IESs, achieving a lot of technical accumulation. This chapter will present the basic information of some representative demonstration projects.

5.1. The Xiong'an nearly zero carbon building demonstration project

The Xiong'an nearly zero carbon building demonstration project, constructed by State Grid Xiong'an Integrated Energy Service Co., Ltd, is a seven-story building covering an area of 9942.85 m^2 and located at plot C1-01-06 of the northwest corner of Rongdong District in Xiong'an New Area, China. The project is built around the strategic goal of creating a Chinese energy internet enterprise that is internationally competitive, and focuses on implementing the overall concepts of collaboration, sharing, standardization, and efficiency. The project aims to build a clean, perceptible, and intelligent building by utilizing the latest technologies and concepts from the energy and internet fields [140].

The project includes the following main elements:

(1) Building a low-voltage direct current ecosystem that integrates clean energy, energy storage, and direct current lighting, as shown in figure 13. The project utilizes rooftop PV systems to generate electricity and energy storage devices to create a low-voltage direct current lighting system in the building. The system is designed to be efficient, safe, reliable, flexible, and energy-efficient, and is managed using an energy management system to maximize energy savings. The system is designed to maintain energy self-sufficiency, and the entire system is presented as a fully integrated direct current system from the source to the load.
(2) Building a digital intelligent operation and control system based on digital twin technology. The project utilizes digital twin technology to create a three-dimensional model of the Rongdong Power Supply Service Center, which includes the building's environment, workspaces, and equipment spaces. The project installs 1154 perception devices to create a digital intelligent operation and control system that includes four functions: building overview, green operation, situational awareness, and quality control. The goal is to create a fully perceptible digital building that focuses on smart production and smart living.
(3) Creating a human-centered and intelligent office space. The project is designed to create an intelligent office space that is centered around human needs and is environmentally friendly. The building's equipment is powered entirely by electricity, and the entire building is interconnected through an all-electric system, resulting in zero fossil fuel consumption.

Overall, the project is a showcase for China's commitment to sustainable development and is an important step forward in the country's efforts to create a greener and more sustainable economy.

5.2. The integrated smart energy project in the beautiful village of Xiaogang

The integrated smart energy project in the beautiful village of Xiaogang, led by China National Nuclear Corporation, combines smart energy with rural development. It utilizes renewable resources such as solar

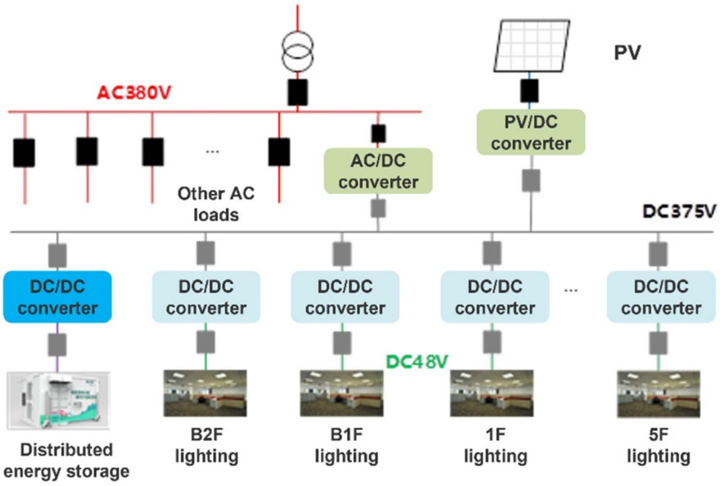

Figure 13. The low-voltage DC system scheme.

energy, geothermal energy, water sources, and straw to develop comprehensive smart energy projects such as ‘energy + ecology’ and ‘energy + agriculture’. The project aims to promote industrial development, ecological construction, and digital rural development by providing clean energy directly to households and village-level enterprises, constructing new energy bases, and consolidating multiple small-scale projects into larger units. The project also integrates government, energy, and community network data to convert it into economic activity and benefits.

The overall implementation of the project includes the following aspects. First, building an eco-friendly village by using renewable resources such as solar energy, geothermal energy, and water sources, planning multiple energy elements, and achieving integrated intelligent management to provide clean energy for the village, achieving 100% clean energy use, and building a zero-carbon village. Figure 14 shows several typical subsystems. The project reduces carbon dioxide emissions by 15 803 tons, sulfur dioxide emissions by 630 tons, and nitrogen oxide emissions by 350 tons annually. Second, building a smart village by integrating big data, cloud computing, and the IoT into key areas such as village governance and people’s livelihood through the Tian Shu Yi Hao comprehensive smart energy management and service platform. Based on the energy network platform, the project establishes government and community networks to achieve ‘three-network integration’. Connecting Tian Shu Cloud with related high-quality platforms achieves energy network integration with government and community networks, strengthens information technology construction in areas such as village affairs, education, medical care, elderly care, tourism, and business, and meets the demands for digital rural development. Third, building a happy village by constructing a green energy cultural corridor, increasing tourism scenes, and improving tourism quality. The village collective and villagers participate in project development through resources such as land and roofs, including the construction of agricultural PV projects and water surface and rooftop PV projects, which provide rental income to the village collective and villagers annually, equivalent to 15% of the annual year-end dividends of Xiaogang Village. The ground source HP saves the village 100 000 Yuan in electricity costs annually and reduces electricity costs by about 45%. The household PV system saves residents half of their annual electricity costs, effectively improving their sense of happiness and achievement. Fourth, building a strong village by carrying out ‘energy + agriculture’, integrating ‘agricultural photovoltaic and water cultivation’ to achieve large-scale and industrialized application, expanding the comprehensive utilization industrial chain of straw, and promoting the electrification and unmanned transformation of agricultural machinery to improve the modernization and scientific and technological level of agricultural production [141].

The project aims to use clean energy to drive industrial development, promote ecological construction through green energy and energy efficiency, and promote digital rural development through intelligent technology. Ultimately, it seeks to achieve a beautiful socialist new era of high-quality and efficient agriculture, livable and business-friendly rural areas, and prosperous farmers. By directly providing clean energy to households and village-level enterprises, the project enables rural areas to directly enjoy economic, green, and low-carbon energy consumption. At the same time, the project creates profits for the construction of rural revitalization and achieves a balance of interests between enterprises and rural areas.

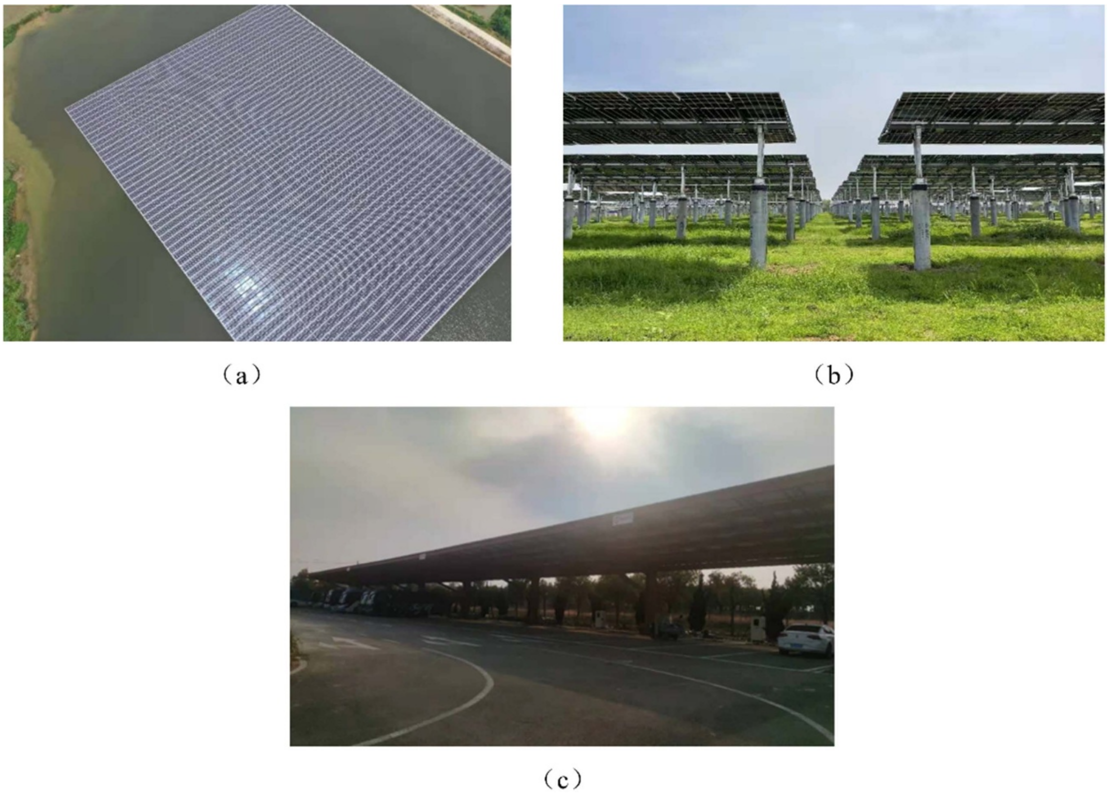

Figure 14. Several typical subsystems: (a) floating photovoltaic system on the water surface of Majiaba Reservoir, (b) agricultural photovoltaic complementary power generation system, (c) photovoltaic carport at Xiaogang Village Visitor Center.

5.3. Active distribution network in Yanqing, Beijing

The Yanqing County in Beijing, China is a region that is rich in renewable resources and has the largest micro-grid demonstration cluster in the country. Due to its high penetration rate of renewable energy, it provides favorable conditions for the construction of an active distribution network demonstration project. The power distribution network in Yanqing has been transformed by way of subarea supply, with a partitioned power supply system that includes DC power distribution to increase cable transmission capacity. DC buses in the DC load area are connected to DC access points in AC load areas to support each other [142].

The demonstration project in Yanqing adopts an energy stratified control strategy to enhance the optimized configuration capabilities of energy transmission networks and the ability to absorb distributed energy. This results in improved power quality and reliability for users, as well as increased utilization efficiency of distribution network equipment. The energy system is stratified and hierarchically balanced by regional autonomy and global optimization.

The entire energy system is designed to support flexible and secure access to distributed power, including the ability to use controllable resources on the user side for coordinated control. Various forms of energy are used to tame new energy fluctuations, enabling the high permeability of distributed new energy demonstrations. In addition, a big data platform based on the energy center of energy management has been built to implement many functions using large data technology, such as distributed energy prediction and user behavior analysis, as shown in figure 15.

5.4. Demonstration of Disneyland Resort in Shanghai

The Shanghai Disney Resort is the first resort in the world to use distributed power technology. This technology involves using natural gas to generate power which is then distributed in three parts. The first part is used to provide power support for recreational facilities in the park, the second part is used to heat water which is then provided to kitchens and hotels, and the third part provides the reaction conditions for chemical reaction refrigeration. By using this energy gradient utilization model, the resort can effectively reduce energy consumption and take full advantage of energy, resulting in a primary energy utilization rate of over 80%.

The project is designed to integrate the energy station centralized control system and the user side energy management system to ensure that all systems in the station are always in efficient operation, as shown in figure 16. The project also adopts cold and hot peaking equipment to meet the energy demand of the user

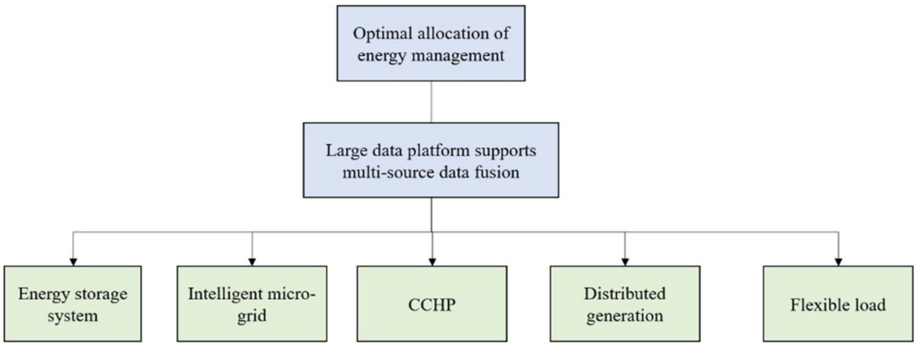

Figure 15. Energy structure of Yanqing County.

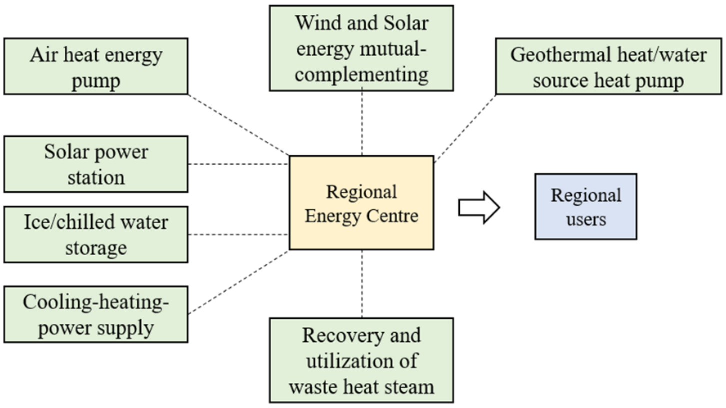

Figure 16. Energy structure of the demonstration project.

side in different periods, and the use of large temperature difference refrigeration technology reduces the overall energy consumption of the system and improves the efficiency of the equipment. Additionally, the project has a black-start function that can ensure the safety of users in the energy system area in the event of a regional grid failure.

Overall, the distributed power technology used in the Shanghai Disney Resort is an efficient, environmentally friendly, and energy-saving way of supplying power to the park. It improves the regional power consumption mode and protects the safe operation of the power grid in the core area. It also avoids over-reliance on energy supply outside the region and plays a strong supporting role in the regional energy network at critical moments [143].

5.5. Tianjin Zhongxin Ecology City Demonstration Project

The Tianjin Zhongxin Ecology City Demonstration Project is a flagship project of cooperation between the governments of China and Singapore. It showcases an IES that effectively utilizes cold, heat, and electricity through the form of a micro-grid. The micro-grid has a comprehensive energy source that integrates multiple energy input, product output, and energy conversion units, as shown in figure 17.

The energy supply ratio of the ecology city is as follows: renewable energy accounts for 16.22%, of which solar energy accounts for 2.33%, wind accounts for 6.84%, geothermal and HP accounts for 7.05%, waste heat accounts for 4.05%, and power plant waste heat (recycled water waste heat) accounts for 3.6%. Biogas (garbage and sludge) accounted for 0.45%. Clean energy accounted for 79.53%, of which distributed energy (triple cooling, heating, and power supply) accounted for 0.24%, gas accounted for 8.82%, power plant steam accounted for 17.97%, and urban power grid accounted for 52.5% [144].

One of the key features of the energy system in the Tianjin Eco-City is the 10 kV energy microgrid that is constructed from a parking lot PV power generation system, a new energy storage system, and a cold/hot/electrical combined system powered by natural gas. This system realizes the complementary advantages of different distributed power sources and helps to optimize the use of distributed power sources. The widespread use of micro-grid can reduce the price of electricity and maximize the economic benefits for users.

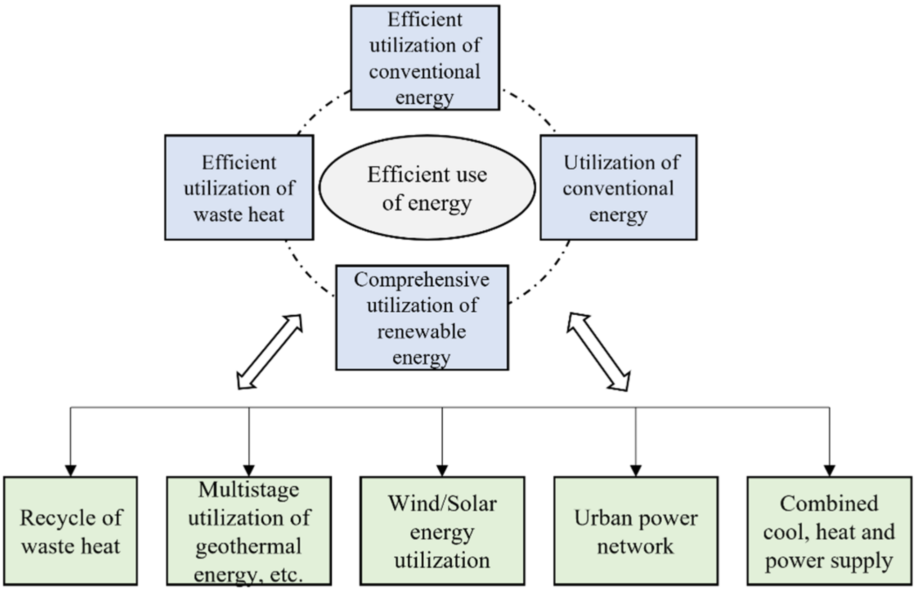

Figure 17. Energy supply of the project.

Based on the PV system of the four buildings in the Animation Park, four independent optical storage micro-grid systems will be set up respectively. It can increase the utilization of PV and improve the reliability of power supply for important loads. The flexible operation mode improves user-side power supply reliability, and users can utilize the difference in the price of peak-to-valley power to run in micro-grid mode.

In summary, the Tianjin Zhongxin Ecology City Demonstration Project showcases an IES that effectively utilizes multiple energy sources and optimizes the use of distributed power sources. The use of a micro-grid system reduces the price of electricity and maximizes the economic benefits for users. The project is a great example of how sustainable energy solutions can be implemented on a large scale to help build a cleaner, greener future.

5.6. Chongming Island Demonstration Project

The Chongming Island Demonstration Project is a comprehensive project that aims to build a ‘zero-carbon-input intelligent international ecological island’ and study the integrated solution of Chongming Island Smart Grid. The project is characterized by large-scale renewable energy sources contracted by State Grid Shanghai Electric Power Co. Ltd and Guodian NARI Technology Co. Ltd.

Chongming Island has abundant renewable energy sources, including wind energy, solar energy, biomass energy, tidal energy, geothermal energy, etc. The project can realize the safe on-grid and consumption of various renewable distributed power sources, as shown in figure 18. Through the construction of a flexible and intelligent power system, the project can achieve industrial, commercial, energy-supply systems for electric vehicles around the island, and ecological agriculture.

The project has completed the engineering application of the first set of megawatt-grade sodium–sulfur energy storage power stations. It has also achieved friendly interaction between users and the grid, fully exploring the potential of renewable energy. The demonstration project has proved that multiple energy coordination can effectively promote the coordinated development of environment and economy, and its construction concept and successful experience have played a good demonstration role for China’s development and construction of ecological civilization [145].

5.7. The regional smart grid demonstration project in Hainan

The regional smart grid demonstration project in Hainan was implemented to address several challenges faced by the power grid in Hainan. The grid’s ability to defend against natural disasters was poor due to frequent typhoons, thunderstorms, and floods. In addition, the grid was unable to consume intermittent renewable energy, and fossil energy self-sufficiency was insufficient. As an international tourism island, Hainan aimed to develop electric vehicles as a major means of reducing pollution, but the orderly charging of vehicles or integrating charging stations into the operation control of the grid was a challenge [146].

To tackle these issues, the project integrated various elements on a large scale based on actual demand. The project included smart dispatch, intelligent disaster warning system, smart distribution network

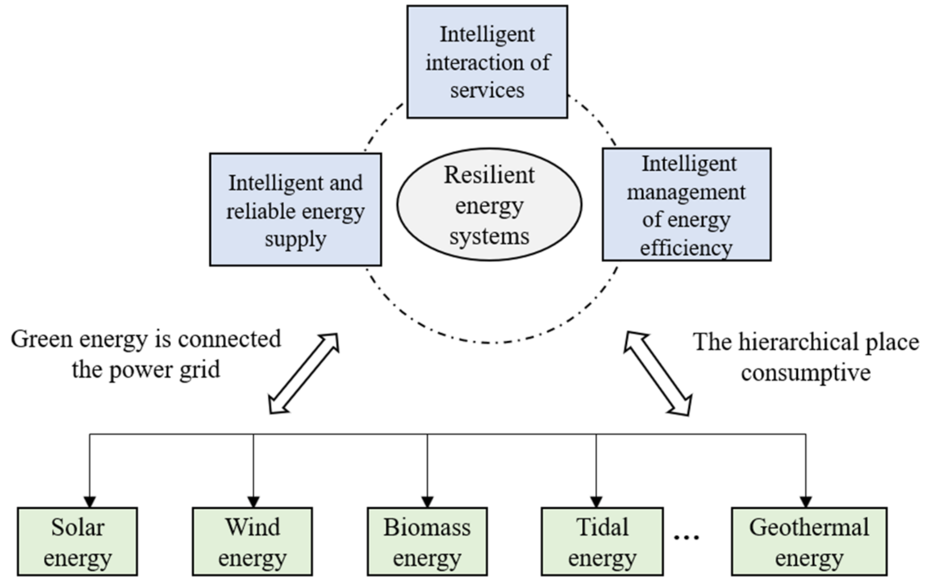

Figure 18. Energy management method of Chongming Island Demonstration Project.

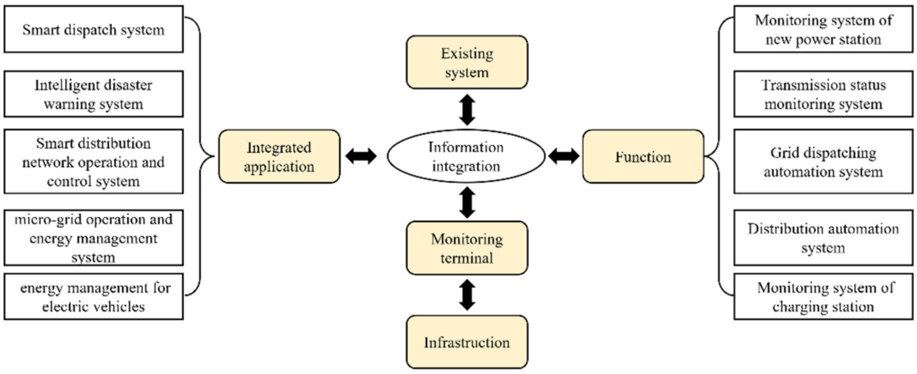

Figure 19. Technical framework of regional smart grid.

operation and control system, micro-grid operation and energy management system, and electric vehicles management system, as shown in figure 19.

The smart dispatch system was based on existing wind and PV power stations and automation systems in Hainan. The system integrated the active and reactive power control system of wind and PV power stations and the optimization control system of active and reactive power on the dispatching side. The aim was to minimize the cost of power generation and improve the availability of intermittent energy stations.

The intelligent disaster warning system was designed to establish risk warning and decision support plans based on the status information of existing equipment and meteorological environment information. The system ensured that operators were timely informed of changes in the trend, scope, and danger level of damage caused by natural disasters. It also helped operators understand the potential types of equipment faults and danger levels through quantitative and qualitative descriptions, providing corresponding decision support.

The smart distribution network operation and control system was implemented based on the distribution automation system platform. The system connected with production management systems, geographic information system (GIS) platforms, marketing management systems, and metering automation systems through standardized interfaces. This enabled information integration and application of the intelligent distribution network, optimizing the operation and self-healing control of the distribution network.

The micro-grid operation and energy management system analyzed demand and issued control instructions to achieve energy balance and optimal operation of the micro-grid.

Finally, the energy management of charging/replacement stations for electric vehicles was strengthened through combining existing system information with processing, analysis, and statistics.

Table 4. The key features of all the demonstration projects.

Exemplary project	Type of load	Type of renewable energy	Scope	Goal
The Xiong'an nearly zero carbon building demonstration project	Electricity	Solar	Building level	Zero carbon
The integrated smart energy project in the beautiful village of Xiaogang	Cold, heat, electricity, vehicle charging, and agriculture	Solar, wind, biomass, geothermal energy	Village level	Zero carbon
Active distribution network in Yanqing, Beijing	Cold, heat and electricity	Solar, geothermal energy	County level	High quality and reliable energy supply
Demonstration of Disneyland Resort in Shanghai	Cold, heat, electricity, and gas	Solar, wind, geothermal energy	Regional level	Efficient and reliable energy supply
Tianjin Zhongxin Ecology City Demonstration Project	Cold, heat, and electricity	Solar, wind, geothermal energy	County level	Uninterruptible power supply for important loads and economic energy costs
Chongming Island Demonstration Project	Cold, heat, electricity, vehicle charging, and agriculture	Solar, wind, biomass, tidal energy, geothermal energy	Island level	Zero carbon
The regional smart grid demonstration project in Hainan	Electricity, vehicle charging	Solar, wind	Provincial level	The grid's ability to defend against natural disasters and consume intermittent renewable energy

By the end of 2021, the project had achieved significant progress. The automation and intelligence level of Hainan's power grid was comprehensively improved, with clean energy installed capacity accounting for 70%. The risk of general or higher-level grid accidents had been fully eliminated, and the average outage time per household had been reduced to 9.88 h [147].

In summary, a brief description of these demonstration projects is shown in table 4.

6. Summarizing and looking forward

IESs provide efficient, clean, and renewable energy supply for regions by coordinating the electricity, heating, and cooling sectors. This review presents and introduces different IES modeling methods, available tools, integrated energy service modes and demonstration projects in China.

In the discussion of IES modeling approaches, we divide the modeling process into demand acquisition, energy subsystem modeling, data simplification methods, uncertainty analysis, scenario analysis and multi-objective decision-making analysis. In the modeling process of IESs, there are various uncertainties that need to be considered. Neglecting these uncertainties can impact the accuracy of the results and result in a lack of robustness in the system. With the development of data science, the combination of data-driven models and engineering models can uncover stochastic volatility not contained in engineering models under actual operating conditions and improve the reliability of parameters. In addition, the combination of data-driven approaches can increase the speed of simulation calculations, and the application of large-scale smart devices makes it possible to monitor energy demand and schedule and adjust energy supply in real time. Exploring modeling approaches with multiple uncertainties may be the focus of future developments.

In the comparison of planning tools, the focus of different tools is presented. These tools greatly support developers in designing energy systems, policy designers in developing energy policies, and operators in coordinating operations. However, there are still areas where these models and methods need to be developed. For example, regional energy demand forecasting is not comprehensive, the ability to simulate the operating state of energy systems during actual operation is inadequate, as is the study of distributed control response of devices. Additionally, the source code of nearly all tools and platforms in China is not publicly available, with only a few being open for external usage. The transparency of these tools remains a significant concern.

From the development of China's integrated energy services and demonstration projects, we can draw the following conclusions: firstly, in the construction and development of IESs, domestic demonstration projects typically aim to consume renewable energy and efficiently use energy to address the crisis of fossil fuel depletion. Secondly, the coordination, optimization, and control of various energy sources are critical technologies for achieving the above goals. Therefore, energy management centers or platforms are usually used to control energy consumption in various demonstration projects. Even large-scale systems are managed in a hierarchical and zonal manner to achieve coordinated optimization of various energy sources within a region. Thirdly, key equipment for the conversion and coordination of cooling, heating, electricity, and gas energy typically uses micro gas turbines, forming local systems for cold, heat, and electricity. Joint optimization strategies for cold, heat, and electricity are developed through energy management centers.

In addition, there are still some shortcomings in the development of China's IES. Firstly, policies currently have a significant impact on the development of the renewable energy industry, and energy prices and tax systems do not create a fair competitive environment for renewable energy, which hinders the sustainable development of the industry. Therefore, it is necessary to further improve preferential policies such as prices, finance, and taxation that support the development of renewable energy to promote the comprehensive utilization of energy resources. Secondly, it is important to establish regional energy management centers. Energy management centers are an important strategy for achieving comprehensive energy utilization and energy conservation and emission reduction. Concentrating various energy sources in a certain area can achieve complementary advantages of various energy sources, effectively control energy flow, transfer energy to a quantified load side, and switch between different operating modes and methods to enrich the energy system. Thirdly, the demand-side response mechanism needs to be improved. Demand-side response is an effective measure to fully utilize the efficiency of IESs and an important measure to improve the stability and efficiency of the entire energy supply market. A sound demand-side response mechanism can create better conditions for demand-side management and fully leverage the effectiveness of demand-side response to form a virtuous cycle. Finally, promoting the development of new energy equipment is essential. The stable and reliable operation of IESs requires new energy equipment as support, such as developing new energy management devices like energy routers, to achieve multi-energy flow monitoring and control, ensuring energy quality, and stable transmission.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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