

Data center integrated energy system for sustainability: Generalization, approaches, methods, techniques, and future perspectives

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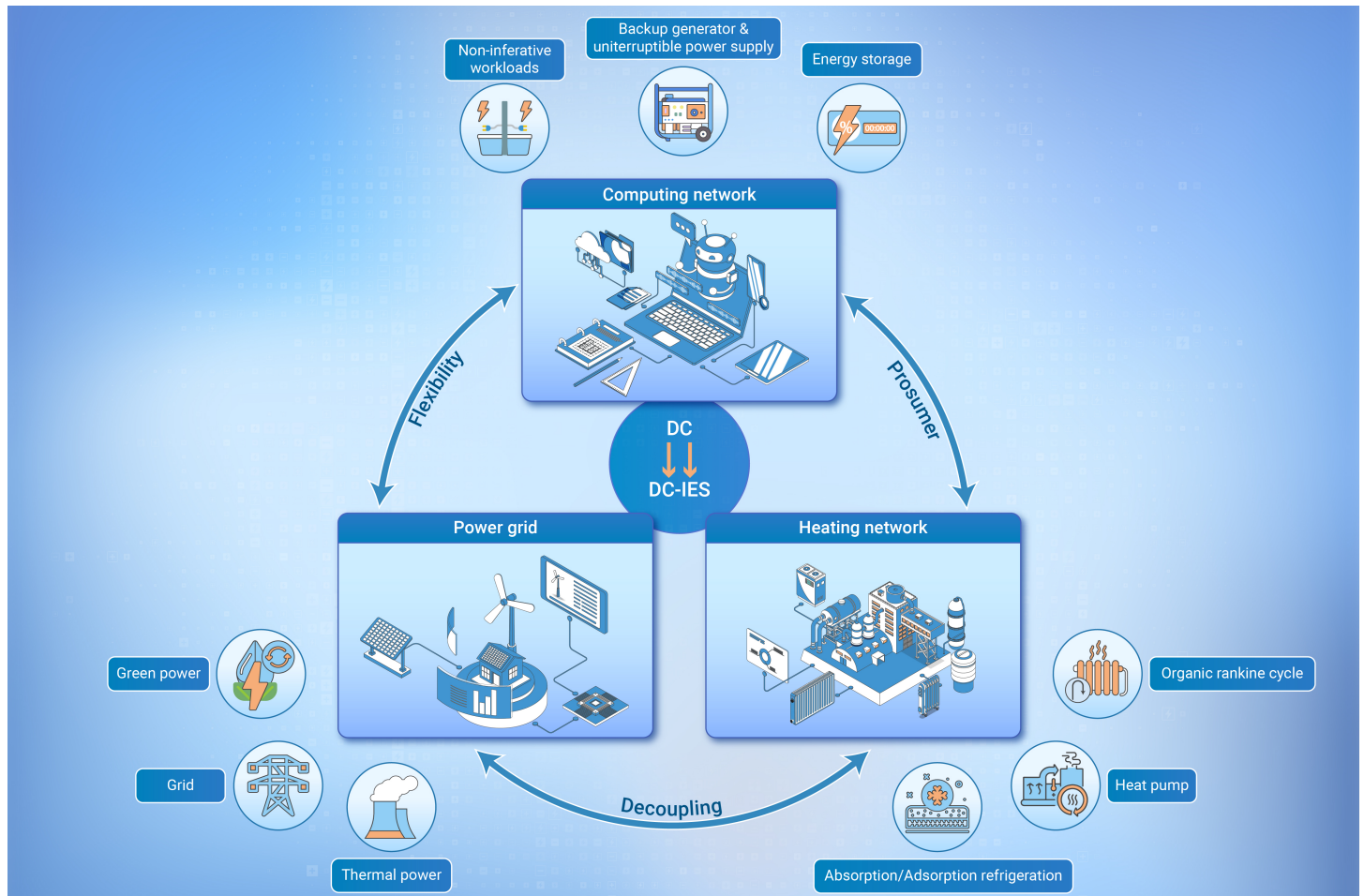
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GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Data center merges integrated energy system by establishing a cohesive energy chain.
- Data center integrated energy system exemplifies the global optimization potentials.
- Innovative research between computing, power, and heating are reviewed.
- Generalization, approaches, methods, techniques, and future perspectives are investigated.

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The increasing prominence of data centers (DCs) in the global digital economy has raised concerns about energy consumption and carbon emissions. Simultaneously, the rapid advancement of integrated energy systems (IES) has enabled DCs to efficiently harness clean energy and waste heat, contributing to sustainability. A concept of data center integrated energy system (DC-IES) is introduced in this paper, and its generalization, approaches, methods, techniques, and future perspectives are scrutinized on the utilization of renewable energy, recovery of waste heat, construction of producer and consumer and diversity of system architecture, as well as optimization solutions in DC-IES planning and design. The evaluation indicators and optimization objectives of DC-IES are also discussed from perspectives of energy, water, economy, environment and reliability. Furthermore, innovative models are proposed for DC-IES to actively engage in the interaction between computing networks and power grids as well as heating networks respectively, while also emphasizing their associated research through the technical principles, participating elements and benefit impacts. It reveals that the integration of non-interactive workloads in the computing network, along with the utilization of flexible resources from diesel generators and uninterruptible power supply, as well as the implementation of waste heat recovery technologies such as heat pumps and absorption refrigeration systems, will significantly enhance the planning and operation of DC-IES. Finally, a series of challenges and future perspectives related to the reliability and cost-effectiveness encountered in the optimization of DC-IES are revealed.

INTRODUCTION

The production, utilization, storage, and flow of data and their resulting consumption and carbon emissions are expanding rapidly worldwide.¹ The convergence of traditional industries with cutting-edge technologies such as cloud computing, big data, the Internet of Things, mobile internet, and artificial intelligence has ushered in the era of the digital economy.² As the cornerstone of the digital economy, data centers (DCs) play a crucial role in supporting and driving various digital industries worldwide. With the rapid advancement of technology and increasing reliance on digital infrastructure, the scale of DCs is continuously expanding worldwide. The rack market of global DCs is expected to grow from \$ 4.4 billion in 2022 to 6.6 billion in 2027, at a compound annual growth rate of 8.7% during the forecast period.³ In parallel, particularly within the context of sustainable energy development, the energy consumption and carbon emissions associated with the construction and operation of DCs have gradually garnered global attention from scholars and governments. In 2020, global DC electricity consumption exceeded the

total power consumption of countries such as South Africa, Egypt, and Argentina.^{4,5} It is not arduous to envision, as multiple pieces of evidence indicate that the escalating dependence on data for pre-training and learning means in the large language models (LLM) will necessitate even greater energy consumption and carbon emission.^{6,7} Recent predictions state that the energy consumption of DCs is set to account for 3.2 % of the total world's carbon emissions by 2025.^{4,8} Furthermore, the storing of digital data is set to create 14% of the world's emissions by 2040, around the same proportion as the US does today.⁹ Correspondingly, the research publication bibliometric analysis made in the Scopus database (data as of November 2023, search keyword: data center, on Scopus database) reveals that the proportion of research papers related to energy has grown rapidly and with its volume accounting for 50% of the total paper in the last three years.¹⁰ With the rapid growth of DCs, the issues of energy supply, efficiency improvement, and carbon emission reduction have become hot topics.

The recent decade has witnessed meanwhile the subtle transformation in energy utilization within DCs, driven by technological advancements in various forms of renewable energy, and the imperative for sustainable development and economic efficiency.^{11,12} In addition, as an effective research method, burst keywords for DC research reveal that, in the early years of the 21st century, scholars began to focus on thermal management and DC cooling, with research emphasizing the critical aspects of refrigeration systems in ensuring the safe and stable operation of DCs.^{13,14} Subsequently, research interests gradually shifted towards areas such as green computing and power consumption optimization, reflecting a growing emphasis on IT systematization and energy efficiency in DCs.^{15,16} In recent years, efforts to mitigate these impacts encompass the exploration and implementation of improvement of rack utilization ratio,¹⁷ renewable energy sources,^{18,19} recovery of waste heat,^{20,21} intelligent operational cooling strategies,^{22,23} as well as the adoption of diversified energy storages²⁴ in DCs planning and operation. These efforts also can be found in a DC sustainability survey report from uptime institute and through the research bibliometric analysis.²⁵ Wherein, energy efficiency improvement, energy utilization, and green computing are currently the main research keywords revolving around DCs, these are intimately related to integrated energy systems (IES). In other words, the convergence of DCs and IES is beginning to emerge within the new energy system, called the data center integrated energy system (DC-IES) in this paper, indicating a growing integration of renewable energy, efficiency improvements, economic enhancements, and sufficient flexibility.^{26,27} And the energy consumption of DCs appears to have numerous potential connections with the supply characteristics of IES. The traditional DC is characterized by the integration of information input and electricity consumption, generating

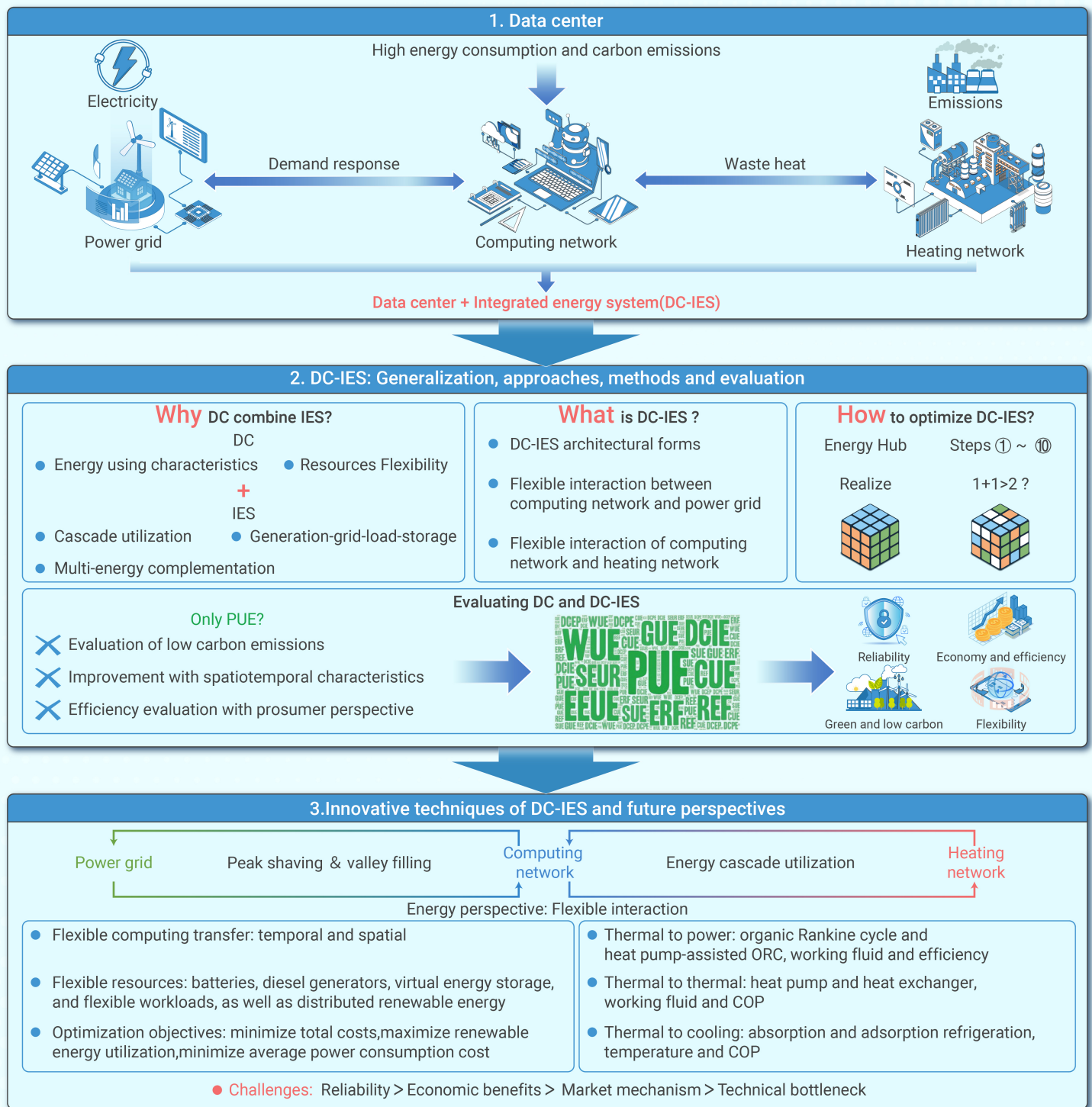


Figure 1. Logical structure of the paper

computational output. In contrast, DC-IES introduces additional renewable energy inputs at the source and the reuse of low-grade waste heat in DCs, and the task load transfer and flexibility are attracting interest.

Firstly, the energy consumption characteristics of DCs are well aligned with the energy generation of IES. While IT equipment in DCs requires a significant amount of electricity, it also necessitates a substantial cooling load. In addition, the capacity features of both electricity and cooling loads remain equal nearly, which perfectly aligns with the energy supply characteristics of IES.²⁸ The cooling load often accounts for 20% to 60% of the energy consumption in DCs, and the multi-stage low-carbon planning approach of DCs with the IES is shown to be more reasonable and economical.²⁹

Secondly, underutilized energy facilities like diesel generators and energy storage batteries in DCs can be activated and seamlessly integrated with the local power grid to facilitate renewable energy consumption in DC-IES.³⁰ The installation of these backup facilities in large-scale DCs is very significant, as it is equivalent to the IT power capacity within DCs. Thirdly, with the rapid application of pre-training in LLM, the number of transferable workloads in DCs is gradually increasing. By utilizing and redistributing these computing tasks, DCs can actively participate in energy demand-side management within IES, aiding in load balancing during peak periods and bridging energy gaps in times of low demand.³¹ Fourthly, the abundant low-temperature waste heat in DCs can be utilized through technologies such as heat pumps

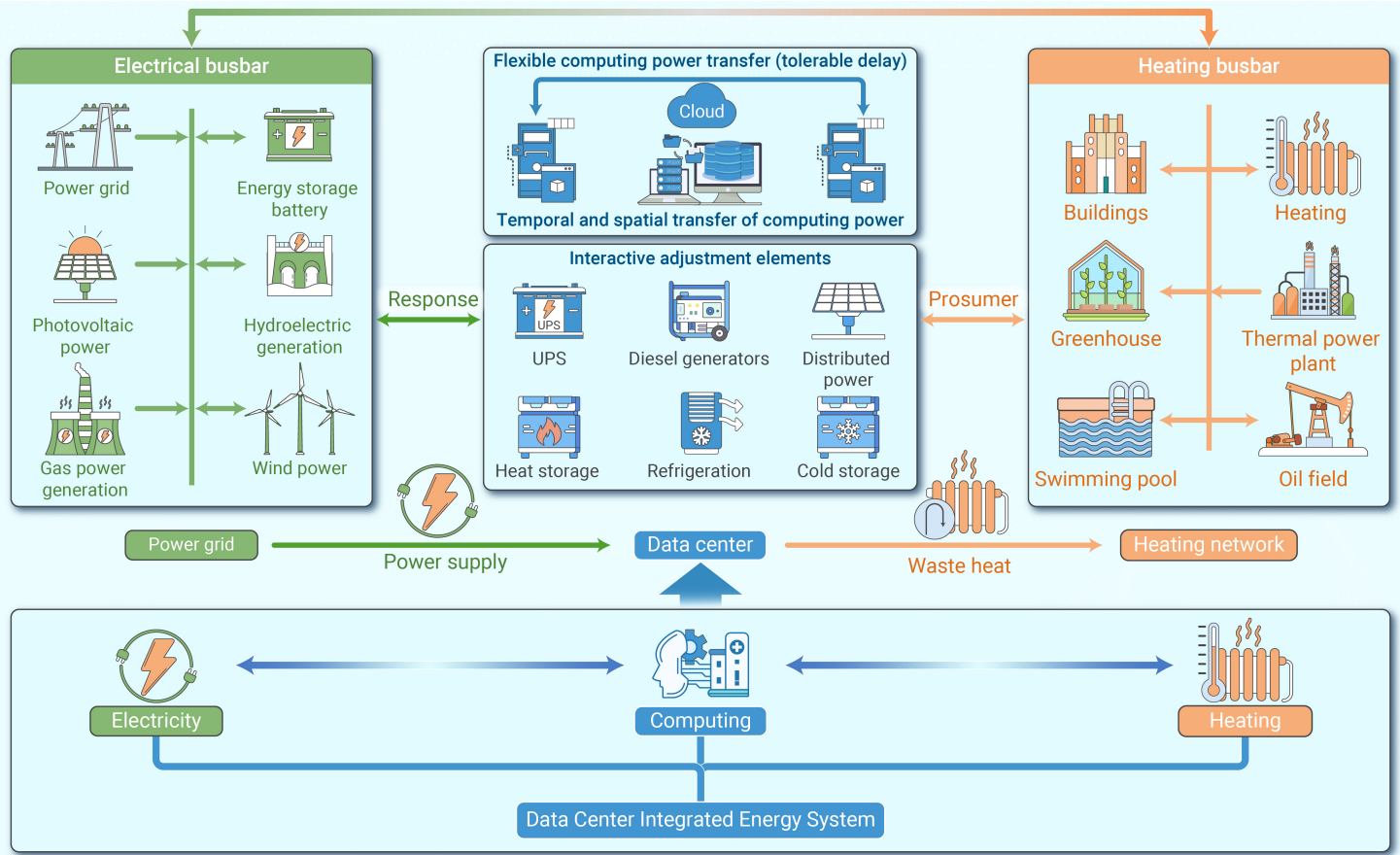


Figure 2. DC-IES diagram

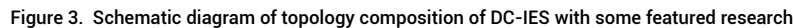
and efficient heat exchangers, establishing a symbiotic relationship between producers and consumers for comprehensive energy utilization by DC-IES.³² In recent years, a set of studies have exploited and summarized the changes of DCs on waste heat recovery,³³ load shifting,³⁴ flexible resources.³⁵ However, these reviews are conducted from a localized or single-technology perspective nearly, with few addressing the broader patterns in the view of DC-IES, which including power grids, heating networks, computing networks and their coupling effects simultaneously. It is noteworthy that the integrated and interactive optimization across the upstream power supply, midstream IT equipment, and downstream cooling systems in DCs significantly contributes to the overall energy efficiency or economic benefits of DCs. Everything has two sides, the DC-IES model, which advocates for system-level optimization, will pose greater theoretical and market challenges compared to previous optimizations that focused on specific stages or process, such as planning solving the coupling power supply problem of multi-type devices, addressing the benefits distribution of DC-IES under multi-agent games, and ensuring thermal safety during the process of task business migration. These details currently need to be systematically revealed in DC-IES.

The motivation of this paper is to establish a coordinated and interactive concept of DC-IES, review its generalization, approaches, methods, techniques, and future perspectives to address the gap in local optimization and provide an updated overview of new energy efficiency enhancement research in DC-IES. DC-IES encompasses upstream renewable energy supply, midstream energy consumption by computing networks, and downstream energy production through waste energy recovery uniquely. Notably, these three energy streams have traditionally been independently managed in the energy chains of DCs. In this regard, as shown in Figure 1, innovative interaction models of DC-IES, including flexible interactions between computing networks, power grids and heating networks are analyzed, and their generalizations, approaches, and methods are revealed and investigated. The planning and operational optimization process of DC-IES is structured into ten steps in the paper, delineating the realization of DC-IES. Additionally, it discusses the evaluation indicators from various perspectives such as

energy, water, economy, environment, and reliability. Furthermore, this paper proposes innovative techniques and models to enhance interaction between computing networks and power grids as well as heating networks respectively within DC-IES, while also uncovering a range of challenges and future perspectives in optimizing DC-IES.

DC-IES: GENERALIZATION, APPROACHES, METHODS AND EVALUATION DC-IES and its generalization and approaches

IES refers to an energy production and consumption system that organically coordinates the generation, conversion, transmission, distribution, storage, and consumption of energy throughout the planning, construction, and operation processes.³⁶ As shown in Figure 2, different from IES, DC-IES has significant characteristics in terms of energy. It is not only based on energy cascade utilization, multi-energy complementary, and generation-grid-load-storage approach^{27,35} but also closely integrated with the operational and computational characteristics of DCs. Different from DCs stable power supply mode of traditional grids mainly driven by thermal power plants, DC-IES incorporates a significant proportion of fluctuating renewable energy sources. Therefore, the DC-IES is expected to maintain high energy reliability to ensure continuous operation and fulfill the data-centric computational and storage demands. Secondly, the distinctive attributes of LLM, such as intensive computational power for pre-training and non-real-time interactive tasks with transferable time and space properties, result in new challenges for DC-IES when engaging with the power grid and heating network. The third point is that, unlike minimal heating requirements, DCs only have significant cooling load demands unless the needs of surrounding heat users are taken into consideration.^{37,38} Therefore, unlike traditional DCs, the involvement of diverse and extensive heat and cold users in DC-IES allows for the establishment of a prosumer pattern (producer-consumer). Consequently, DC-IES exhibits greater flexibility in terms of energy, economic, and environmental perspectives. Taking China as an example, it is estimated that the installed power of DCs has reach 16.25 GW by 2022, accommodating a total of 6.50 million standard racks. Assuming an approximate rack utilization ratio of 50%, these



The second aspect of flexibility involves the versatile interaction between the computing network and the heating network within DC-IES. The opera-

Architectural paradigms. The optimization of diverse energy conversion devices and their interconnection relationships are crucial when considering the system topology of DC-IES. Under the conventional perspective, there exists a correlation only between upstream energy supply and DCs. From the standpoint of DC-IES research, numerous system architectures remain to be extensively explored owing to the diverse requirements of energy conversion equipment in both upstream energy supply and downstream energy consumption processes of DC-IES, as shown in Figure 3. Generally, in common DC-IES, upstream energy sources such as grid electricity, natural gas, and solar energy are utilized as inputs. These sources are then transformed and integrated through energy conversion devices to meet the cooling, heating, and electrical load demands of DCs and nearby buildings. Heat

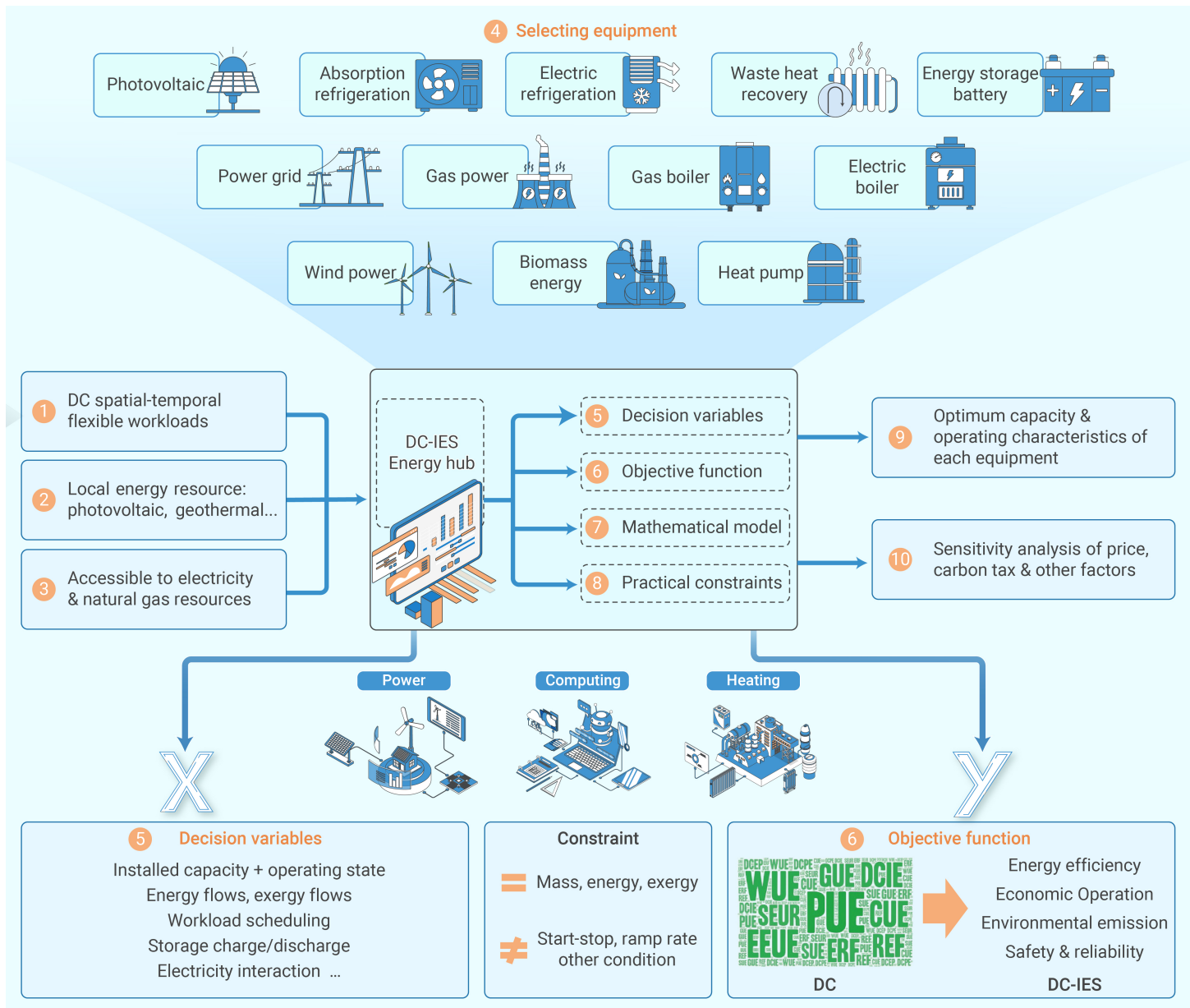


Figure 4. Typical solution process for modeling and optimization of DC-IES

sources from the downstream heating networks can be reused by some low-grade heat-driven equipment. Each energy conversion device possesses its own unique technological and economic characteristics, making the selection of an optimal topology a complex and multifaceted decision-making process. Consequently, many studies have focused on developing various configurations for DC-IES topology based on their research background. For example, for DCs with strict requirements on temperature and humidity, a DC-IES based on proton exchange membrane fuel cells (PEMFCs), integrating methanol-reforming and dehumidification was proposed,⁴⁷ where the adsorption chiller that utilizes waste heat from PEMFC and desiccant air conditioning system are used simultaneously. A combined heat and power (CHP) unit consisting of an absorption chiller was adopted in DC and effectively improving the system energy utilization.⁴⁸ A decarbonized IES for DCs was designed based on hydrogen-water energy,⁴⁹ leveraging solar energy for water electrolysis to produce hydrogen, using fuel cells for electricity generation, and combining waste heat with solar thermal energy for absorption chillers. A novel DC-IES with seasonal synergistic is proposed,⁵⁰ coupling of steam compression refrigeration, heat pipes, and absorption chillers, comparing the cooling energy consumption and energy efficiency of systems both with and without heat pipes. Also, some engineering cases have made relevant attempts to verify their feasibility, economic viability, and environ-

mental friendliness. For instance, a combined cooling, heating and power (CCHP) system has been implemented for one of Tencent's DCs in Shanghai, China. This system generated 8.86 million kWh for heating and 9.63 million kWh for cooling, resulting in a reduction of carbon emissions by 5,018 tons annually.⁵¹ In Finland, Telecity Group operates five DCs with three of them utilizing waste heat in the district heating system to provide warmth to 500 individual houses and 4,500 apartment blocks.⁵²

Planning and operation optimization. Unveiling the intricate multivariable, nonlinear coupling relationships that emerge during the planning and operational optimization of DC-IES is of utmost importance. The optimization research of DC-IES necessitates a comprehensive consideration of the inter-relationships among geographical location, carbon emissions, energy resources, economic benefits, various energy conversion technologies and the flexibility as well as reliability of DCs. Figure 4 illustrates a typical solution process for optimizing DC-IES.^{53,54} The solution process encompasses several crucial steps to ensure optimal performance and resource utilization in DC-IES, summary as follows: (1) Accurately depicting the computing capacity, power and cooling requirements, as well as typical daily demand of the surrounding fields in general, which involves understanding the spatial and temporal transferability of DC-IES business operations;³⁵ (2) Conducting investigation and analysis of both internal and external energy resource

Key goals of data center in different stages in China

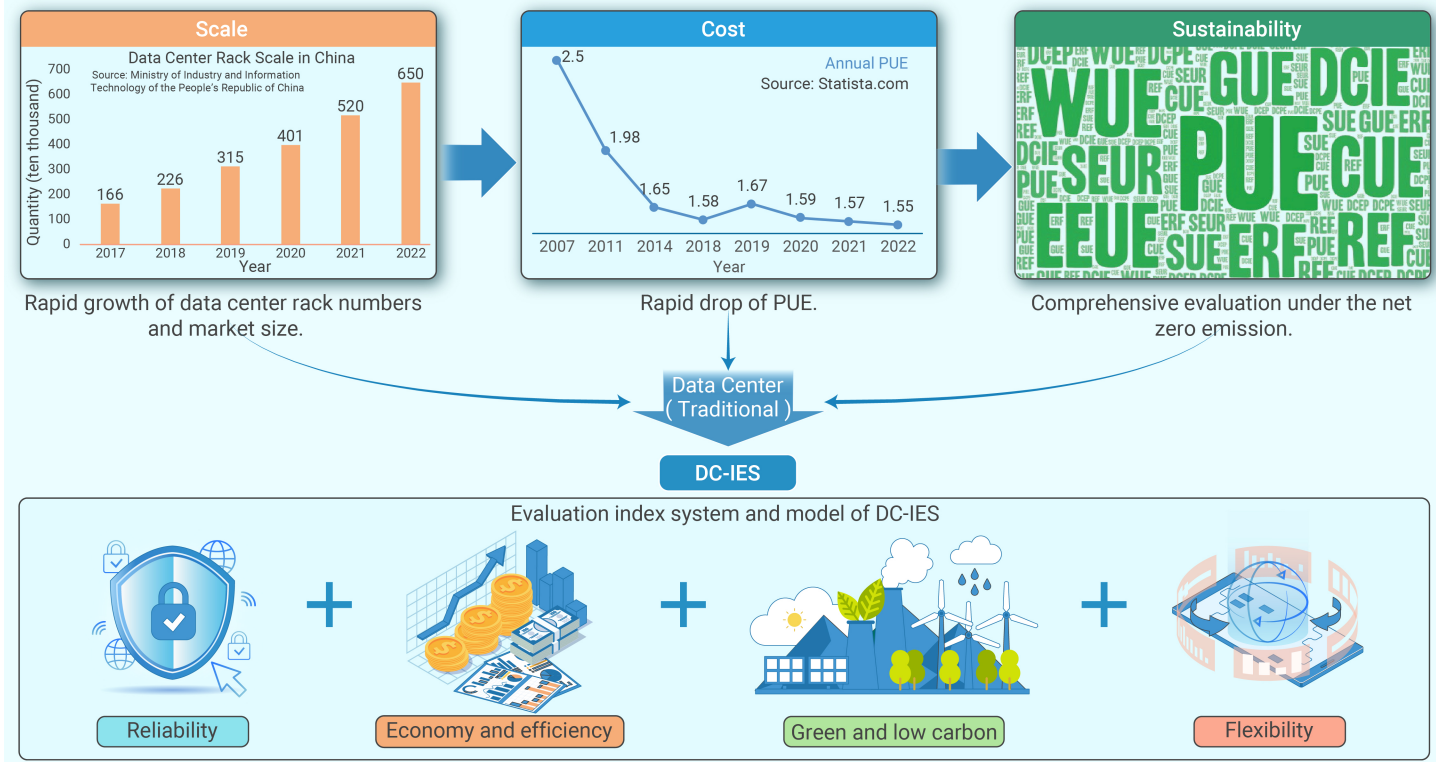


Figure 5. Key goals of DC in different stages in China

endowments of DC-IES. This step includes assessing available power grid capacity, natural gas resources, heat sources, as well as distributed green energy options;⁵⁵ (3) Performing an analysis of energy consumption price characteristics, which involves studying market prices for electricity, power generation costs, heating expenses, and so forth. These characteristics play a significant role in decision-making processes regarding resource allocation;⁵⁶ (4) Selecting appropriate energy conversion equipment is crucial for optimizing overall system performance.⁴⁷ This involves evaluating various options like electric conversion or thermoelectric conversion technologies based on their efficiency and compatibility with DC-IES requirements; (5) The variables in DC-IES optimization primarily encompass two aspects: the capacity configuration and the operation scheduling of system equipment, including the capacity of each equipment, the hourly cooling, storage charge/discharge,⁴⁸ thermal and electrical output,⁵⁷ workload scheduling⁵⁸ and electricity interaction;⁵⁹ (6) The optimization of DC-IES typically involves solving a multi-objective optimization problem with multi-variable coupling and optimization objectives, the forthcoming text will provide further reviews on evaluation indices and optimization objectives;⁶⁰ (7) Establishing a comprehensive model that ensures conservation of mass and energy while accurately representing the energy conversion characteristics of DC-IES equipment; (8) Describing the equality and inequality constraints associated with each device involved in DC-IES. These constraints include capacity limits for efficient operation, and operational range limits for stability under different conditions, along with unique operational characteristics of each device. Generally, the mathematical programming methods are employed for solution, followed by the utilization of intelligent algorithms or solvers to address different scenarios;⁴⁹ (9) Constructing a closed-loop scheme that integrates all components of DC-IES while considering their interdependencies. By solving this scheme through mathematical modeling or simulation techniques, an optimized solution can be obtained that maximizes overall performance while meeting predefined optimization objectives;⁵⁵ (10) Conducting a sensitivity analysis on the proposed scheme to evaluate its robustness and identify potential limitations or boundaries where it may not be applicable.

In summary, maintaining a constant equilibrium between power supply

and energy demand in DC-IES requires the utilization of established models based on an hourly scale that divides the entire year into seasons (spring, autumn, winter, and summer).⁶¹ It is important to note that current research lacks online scheduling for load and power forecasting in DC-IES. Furthermore, different components within IES such as cooling, heating, electricity, and computing power operate on varying time scales.^{62,63} This presents a multi-time constant problem that necessitates further attention in DC-IES. Additionally, during the planning stage, constant equipment efficiency performance models are typically employed by setting the coefficient of performance (COP) for compression refrigeration at 3.0 and natural gas cogeneration efficiency at 0.4.⁶⁴ However, variations in workload rates or operating condition temperatures can impact the energy conversion equipment's efficiency performance during operational scheduling. In response to this challenge, some scholars have initiated the utilization of variable-condition coefficients of energy efficiency for planning and scheduling of DC-IES.⁶⁵

Evaluation indicators and optimization objectives. Compared to the exponential growth in processed data volume worldwide, the increase in computing power is still insufficient for the capacity of DCs. Therefore, in the early stages, DCs focused more on filling the gap in computing power through rapid construction, especially in countries with fast-paced digital economic development. As illustrated in Figure 5, DCs shifted their focus to economic operations by minimizing electricity consumption and improving system efficiency as much as possible. PUE, as a renowned indicator for evaluating energy efficiency in DCs, plays a pivotal role in optimizing resource utilization and mitigating environmental impact. In 2022, the average PUE of the surveyed DCs is 1.55. This means that 55% of the electricity consumed by IT racks is used for auxiliary systems.

Due to rapid technological advancements and the ever-evolving landscape of market policies and environmental regulations, some shortcomings have been exposed when using PUE to evaluate emerging DC energy systems, including: (1) The PUE fails to provide a comprehensive assessment of overall environmental impacts of DCs and DC-IES. If a DC relies heavily on fossil fuels, its carbon emissions will be much higher than those that use renewable sources, e.g., solar photovoltaic or wind power, both with the same PUE

Table 1. Data center evaluation indicators

Indicators	Full name	Calculation formula
PUE	Power Usage Effectiveness	$\frac{\text{Total Facility Power}}{\text{IT Equipment Power}}$
COPUE	Coefficient of PUE	$\frac{\text{Real PUE of Data Center}}{\text{PUE when the Benchmark Cooling Technology is Adopted}}$
EEUE	Electric Efficiency Utilization Effectiveness	$\frac{\text{Total Facility Power Consumption}}{\text{IT Equipment Power Consumption}}$
WUE	Water Usage Effectiveness	$\frac{\text{Water Consumption}}{\text{IT Equipment Energy}}$
DCiE	DC Infrastructure Efficiency	$\frac{\text{IT Equipment Power}}{\text{Total Facility Power}}$
REF	Renewable Energy Factor	$\frac{\text{Renewable Energy Used and Owned by Data Center}}{\text{Total Power Consumption}}$
SEUR	Stored Energy Used Ratio	$\frac{\text{The Energy Stored in the Data Center Can be Reused}}{\text{Total Power Consumption}}$
ERF	Energy Reuse Factor	$\frac{\text{Total Installed Capacity of Energy Recycling Equipment}}{\text{Original Installed Capacity of Energy Equipment}}$
CUE	Carbon Usage Effectiveness	$\frac{\text{Total Carbon Dioxide Produced By Total Electricity Consumption}}{\text{IT Equipment Power Consumption}}$
DCPE	DC Performance Efficiency	$\frac{\text{Useful Work}}{\text{Total Facility Power}}$
DCeP	DC Energy Productivity	$\frac{\text{Useful Work Produced}}{\text{Total Power Consumption}}$
SUE	Space Usage Effectiveness	$\frac{\text{Area of IT Room}}{\text{Total Area of Data Center}}$
GEC	Green Energy Coefficient	$\frac{\text{Green Energy}}{\text{Total Energy Consumption of Data Center}}$
ITEE	IT Equipment Efficiency	$\frac{\text{Total Rated Capacity of IT Equipment}}{\text{Total Rated Power of IT Equipment}}$
ITEU	IT Equipment Utilization	$\frac{\text{Actual Energy Consumption of IT Equipment}}{\text{Total Rated Power of IT Equipment}}$
DPPE	Datacenter Performance Per Energy	$\text{ITEU} \times \text{ITEE} \times \frac{1}{\text{PUE}} \times \frac{1}{1 - \text{GEC}}$
GUE	Grid Usage Effectiveness	$\frac{\text{Grid Power Used}}{\text{IT Equipment Power}}$
CEC	Comprehensive Energy Consumption	Sum of Actual Physical Amounts of Energy Consumed
PER	Primary Energy Ratio	$\frac{\text{Total Energy Produced}}{\text{Primary Energy Consumption}}$
EE	Exergy Efficiency	$\frac{\text{Total Exergy of the System Output}}{\text{Total Exergy of the System Input}}$
PESR	Primary Energy Saving Ratio	$\frac{\text{Energy Savings Compared to Traditional Systems}}{\text{Energy Consumed by Traditional Systems}}$
ERR	Emission Reduction Ratio	$\frac{\text{Pollutant Emission Reduction Compared to Traditional Systems}}{\text{Theoretical Emissions of Pollutants from Traditional Systems}}$
OEM	On-site Energy Matching	$\frac{\text{Supply Side Power Generation Used to Meet Load}}{\text{Total Power Generation at the Supply Side}}$

values. Therefore, relying solely on the PUE evaluation index to assess DC-IES that widely adopt new energy sources may have significant adverse effects; (2) PUE may not be enough for assessing DCs and DC-IES that involve spatiotemporal load transfers. Spatiotemporal load transfers are often employed to optimize resource utilization, improve fault tolerance, or accommodate varying user demands in DC-IES. However, PUE primarily focuses on measuring the ratio of total facility power to IT equipment power consumption in a black box without considering these internal and intricate load transfer scenarios; (3) Matching the energy efficiency evaluation of DC-IES with PUE poses challenges from a prosumer perspective. PUE only focuses on the electricity usage of DCs, and this creates some mismatches in evaluating DC-IES that employ energy cascade utilization, for example, it is difficult to evaluate the attribution of the benefits from heat recovery using heat pumps in DC-IES and the electricity consumption of heat pumps.

More new indicators have been proposed to compensate for the shortcomings of PUE,⁶⁶⁻⁶⁹ as shown in Table 1. These new indicators such as the Coefficient of PUE (COPUE), Renewable Energy Factor (REF), Energy Reuse Factor (ERF), Water Usage Effectiveness (WUE), Carbon Usage Effectiveness (CUE), IT Equipment Utilization (ITEU) align more closely with our current vision of achieving net zero emissions, as shown in Figure 5. For DC-IES, the indicators related to the economic cost of energy infrastructure construction are the first concern,⁷⁰ and carbon emission reduction has also become a key objective in sustainability.⁶⁰ As a result, various comprehensive evaluation indicators have been developed and implemented.⁷¹ It is worth noting that, in response to the challenges of multi-stakeholder participation and multi-dimensional evaluation faced by DC-IES, the comprehensive performance evaluation system is often established based on the analytic hierarchy process.⁷² These performance involves the view of reliability, economy and

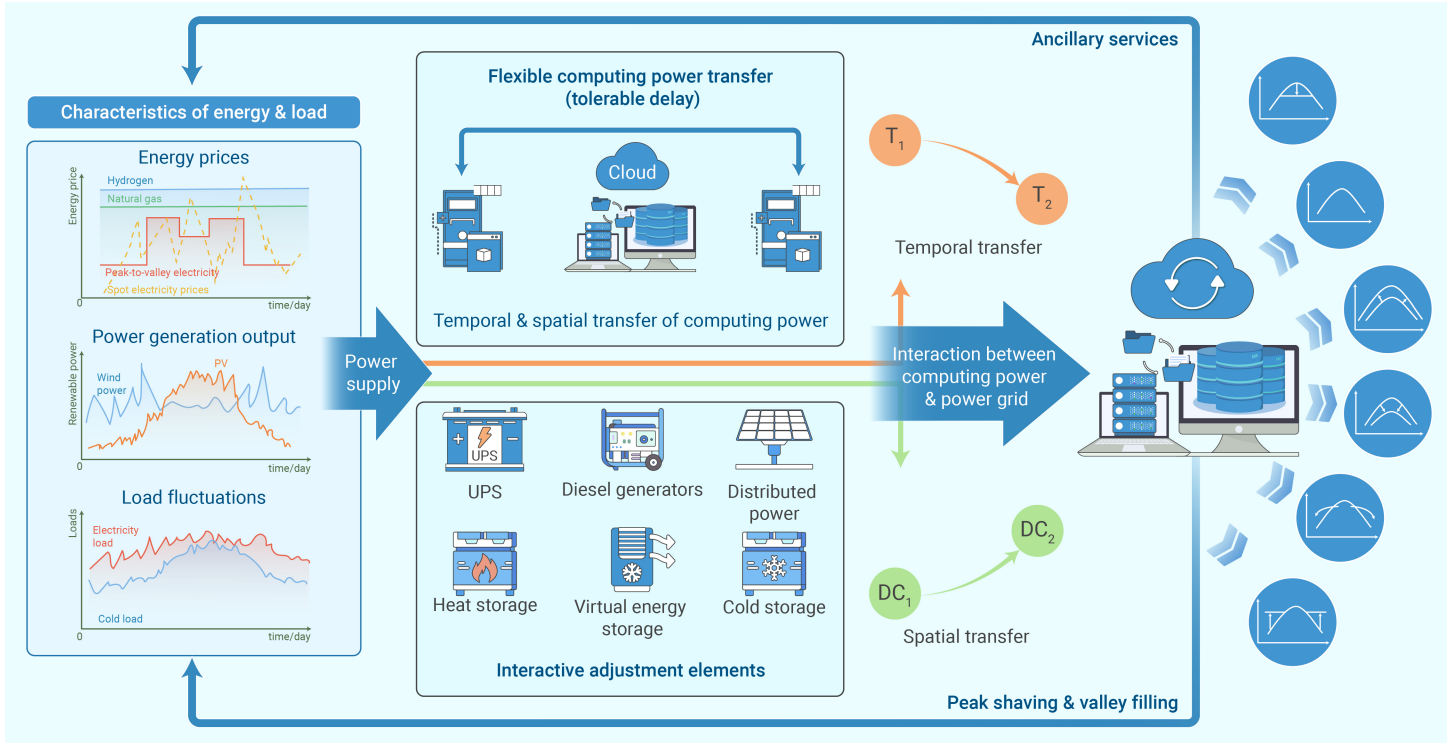


Figure 6. The technical path for the interaction between the computing network and the power grid

efficiency, green and low carbon, flexibility, etc. Here, the classification and weighting of each indicator play a critical role in determining the overall performance superiority or inferiority of DC-IES. In addition, the multi-objective optimization approach also plays an increasingly vital role in enhancing the performance of DC-IES. The approach is based on the principle of generating Pareto front solutions and subsequently employing a rational selection method to derive the ultimate solution among the non-dominant solutions, e.g., a technique for order preference by similarity to an ideal solution, entropy weight method.⁷³

INNOVATIVE TECHNIQUES OF DC-IES AND FUTURE PERSPECTIVES

DC-IES not only optimizes its energy consumption but also contributes to the sustainability and resilience of the power grid and heating network.^{74,75} The incorporation of technologies such as demand response (DR) and waste heat recovery has revolutionized the interactions among computing networks, power grids, and heating networks. This synergy has created novel opportunities for promoting the adoption of clean energy, enhancing energy efficiency, and reducing carbon emissions. The implementation of DR technology allows for a more adaptable management of electricity consumption, as it dynamically adjusts in accordance with real-time supply and demand conditions within an energy system. Using China as a case study, the imperative for enhanced coordination in power grid operations is steadily increasing owing to the rapid development of renewable energy sources. Consequently, China has set a target to achieve a demand-side response capacity ranging from 3% to 5% of its peak electricity load by 2025.⁷⁶ The characteristics of large-scale and resource-rich DCs demonstrate their potential as valuable DR resources in power grids. Furthermore, the waste heat generated during DC operations can be effectively utilized to provide heating for nearby buildings or contribute to district heating networks. If the waste heat from existing DCs in China is efficiently recovered, it has the potential to supply heating for approximately 540 million m², which is equivalent to China's hydrothermal geothermal energy clean heating area (580 million m² as of 2020).⁷⁷ The holistic integration of computing networks, power grids, and heating networks allows DCs to actively engage in the broader energy ecosystem rather than passively consuming resources.^{78,79}

Flexible interactions between computing network and power grid

The active participation of DCs in interactions with the new power system

offers numerous advantages, as they employ various methods to mitigate fluctuations in the power grid and generate profits.⁸⁰ Figure 6 demonstrates the diverse range of available resources within the premises, including batteries,⁸¹ UPS,⁸² diesel generators,⁸³ virtual energy storage systems,⁸⁴ and flexible workloads. These resources play a crucial role in effectively supporting demand-side response activities to address grid congestion through equivalent electrical transfer of time and space, and enabling peak shaving and valley filling operations within DCs and regional power grids. In situations where the power grid faces stress or requires controlled electricity consumption reduction due to environmental concerns or system limitations,⁸⁵ DCs can adjust their computing workloads for power consumption without compromising critical tasks dynamically. This approach facilitates enhanced integration between renewable energy and traditional power generation systems, effectively harnessing available clean energy resources at their maximum capacity while accounting for fluctuations based on weather conditions and other uncontrollable factors.⁸⁶ Large and flexible energy loads are highly desirable demand response resources for maintaining grid stability. For instance, in 2011, numerous DCs across US actively participated in urgent DR initiatives, effectively mitigating potential financial losses amounting to millions of dollars.^{87,88} Moreover, Alibaba conducted a scheduling experiment to divert a portion of workloads from Nantong DC to Zhangbei DC in China, which operates on renewable energy sources. Although this initiative only yielded 150 kWh of electricity, it effectively cultivates a synergistic interaction environment between the computing network and power grid in China.⁸⁹

The interaction between the computing network and the power grid has been investigated in the literature, as summarized in Table 2. These studies encompass various aspects including adjustment scales, adjustment elements, optimization objectives, and technical methods. The adjustment scales of DCs primarily revolve around two types of workloads: batch workloads, which encompass tasks such as data analysis, mining, report generation, and batch file processing, accounting for more than 50% of total workloads;⁹⁰ And interactive workloads, which involve online transaction processing, social media platforms, real-time queries, and searches. The response times of batch workloads tend to be relatively longer compared to interactive workloads, thereby affording them greater flexibility in terms of temporal and spatial adjustments. In one study, the maximum allowable deferral time for batch workloads was found to be 12 hours.⁹¹ Additionally, interactive work-

Table 2. Summary of research on the interaction between computing network and power grid

Ref.	Flexible computing transfer	Flexible resources	Optimization objectives
31	Temporal (✓) Spatial ()	WP, PV	Minimize average power consumption cost (electricity + renewable energy purchase)
92	Temporal (✓) Spatial (✓)	ES, TS, PV	Minimize total costs (investment + operating costs)
99	Temporal (✓) Spatial ()	WP, PV, UPS	Minimize the difference between the actual response of the server cluster and the control signal
101	Temporal () Spatial (✓)	WP, PV	Maximize renewable energy utilization at each DC and minimize total costs
156	Temporal (✓) Spatial (✓)	ES, TS, BPT	Minimize costs (electricity + heat + maintenance cost - DR compensation)
157	Temporal () Spatial (✓)	-	Minimize total cost (electricity + interactive workload delay loss)
105	Temporal (✓) Spatial ()	WP, PV	Maximize operating net profit (data service income - electricity - renewable energy purchase - green certificate cost)
158	Temporal () Spatial (✓)	-	Minimize operating costs (electricity + queuing delay costs)
159	Temporal (✓) Spatial ()	RG, ES	Minimize energy costs (electricity + renewable energy costs + energy storage costs)
160	Temporal (✓) Spatial ()	WP, PV	Increase the penetration rate of renewable energy
161	Temporal (✓) Spatial ()	PV	Minimize total annual costs (investment + maintenance + operations)
162	Temporal () Spatial (✓)	-	Minimize electricity bills
163	Temporal () Spatial (✓)	WD, EV	Minimize operating costs (electricity + workload regulation costs)
164	Temporal (✓) Spatial (✓)	WD, UPS, RG, BG	Minimize operating costs (electricity + workload regulation costs)
165	Temporal (✓) Spatial (✓)	TS	Minimize operating costs (electricity + broadband cost + thermal storage cost)

Abbreviations: BG, Back-Up Generator; BPT, Back Pressure Turbine; DR, Demand Response; ES, Energy Storage; EV, Electric Vehicle; PV, Photovoltaic; RG, Renewable Generator; TS, Thermal Storage; UPS, Uninterruptible Power Supply; WD, Workload Dropping; WP, Wind Power;

loads have high data transmission speeds, offering possibilities for spatial adjustment despite being less flexible in terms of temporal adjustment.⁹² Furthermore, some DCs possess the capability to execute temporal and spatial scheduling of workloads. This is achieved through hybrid deployment techniques, allowing workloads with varying levels of latency sensitivity to be deployed on the same server.⁹³ The scheduling of specific processing time for workloads with varying latency sensitivities can be optimized within the maximum response time allotted to each workload. Particularly with the rapid advancement of LLM, e.g., Google-Bard,⁹⁴ Chat-GPT,⁹⁵ greater amounts of data and computing power can be efficiently transferred in terms of time and space during the pre-training phase, taking into account electricity market conditions, IT energy consumption, and owners' requirements to achieve optimal operational costs. It is reported that the flexibility provided by a single 30 MW DC is estimated to have a value ranging from \$500,000 to \$5,000,000.⁹⁶

Another, diesel generators and UPS batteries play a critical role in supporting DCs by ensuring uninterrupted operation during power interruptions or fluctuations,⁹⁷ moreover, they can also serve as essential components of DC-IES, providing crucial electricity storage capabilities and enabling peak shaving functionalities.⁹⁸ A novel approach for rebalancing frequency deviation at the grid level in isolated power systems was proposed, enabling DCs to participate in fast frequency response service. This approach leverages the combined benefits of on-site UPS batteries and load shifting.⁹⁸ The simulation results depicted that the joint participation of 350 MW DC resources can provide superior performance in mitigating the severity of frequency deviation in ultra-low inertia systems. To eliminate the effects brought by fluctuations in tie-line power after new energy access on the power supply system for DCs, a novel DC tie-line power control method with the occupation of the redundant UPS was introduced.⁹⁹ It reveals that this method effectively mitigates fluctuations in the power of DC park tie-lines even with a high penetra-

tion rate of 32% for new energy sources. Additionally, to address uncertainties related to renewable energy and issues such as wind and solar power curtailment,¹⁰⁰ a geographical workload balancing to maximize on-site renewable energy utilization across multiple DCs was employed. This approach leads to a 17% reduction in brown energy usage and a 22% cost reduction.¹⁰¹ It should be noted that the interaction between the computing network and power grid in DC-IES necessitates the consideration of multidimensional optimization. In addition to traditional objectives, some indicators related to load shifting such as delay losses for interactive workloads or DR compensation were proposed.¹⁰²⁻¹⁰⁴ The implementation of DC-IES significantly enhances energy efficiency and operating expenses reduction, however, the interplay between diverse energy systems may introduce various operational hazards that threaten the reliability of DCs. To encourage users to transfer into high-output periods of renewable energy sources within a certain range so as to improve environmental protection and low-carbon operation of DCs, a green certificate mechanism was introduced while maximizing operating net profit.¹⁰⁵ The results show that after adding subsidy mechanisms, net income increase while carbon emissions decrease by 7.38%.

Flexible interactions between computing network and heating network

The IT equipment in DCs consumes high-quality electricity and generates low-grade heat, which necessitates dissipation through a cooling system.^{106,107} Consequently, the energy consumption of cooling systems used for heat transportation accounts for approximately 20% or even a higher proportion of the total energy consumption within DCs.^{108,109} Moreover, in addition to the limited natural free cooling and transportation options, the recovery and utilization of low-grade heat energy in DCs have attracted significant attention and emerged as a means of synergy between the computing network and the heating network. The low-grade waste heat of computing networks in DCs is generated by various components including

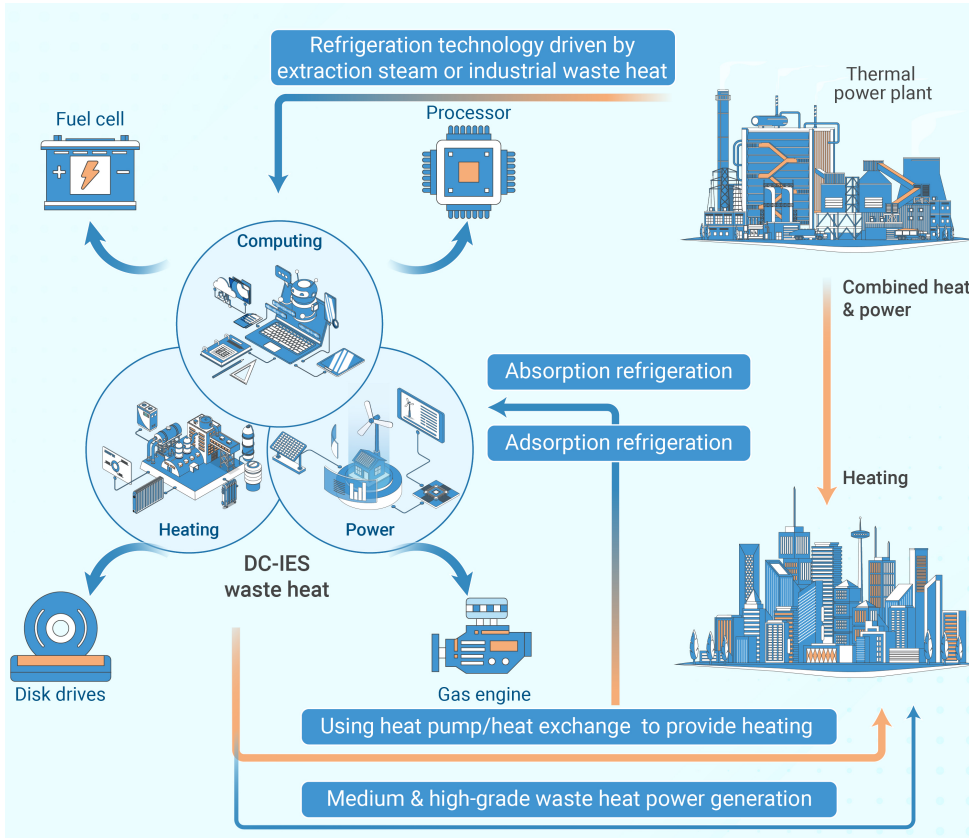


Figure 7. The technical path for the interaction between computing and heating

geous applications, including industry heating, agriculture heating, and wastewater treatment facilities.^{118,119} Furthermore, they also generate profits for DCs. The advancements in heat pumps enable the level of low-grade waste heat from DCs to a high-temperature level that allows its utilization for heating purposes during high-demand periods. Some projects have been implemented by companies like Apple, Microsoft and Meta Platforms, showcasing the effective recovery of waste heat from DCs using heat pumps.¹²⁰ The COP of a heat pump is observed to vary depending on the temperature differences involved in the heat transfer process. Heat pump units driven by waste heat from cooling water in DCs often exhibit a higher COP compared to many air-source driven heat pump units. With the widespread adoption of liquid cooling technology in DCs, even a heat pump directly powered by high-temperature liquid-cooled waste heat from IT servers can achieve a very high COP. The implementation of a water-source heat pump using waste heat from DCs was examined.¹²¹ The findings demonstrate that this scheme achieved a 12.3% reduction in energy consumption for DCs and a 31.2%

processors, disk drives, memory modules, network switches, and storage arrays. Additionally, energy conversion equipment such as diesel generators, fuel cells and gas engines used in DC or DC-IES also emit a significant amount of medium-grade waste heat. The waste heat can be utilized for heating nearby buildings using advanced technologies like heat pumps and heat exchangers, or for generating power through advanced heat power generation technology like organic Rankine cycle (ORC).¹¹⁰ Refrigeration technologies, such as absorption and adsorption refrigeration, utilize steam extraction or waste heat from thermal power plants or industrial processes close to DC to simultaneously fulfill a portion of the cooling requirements for DCs. Essentially, such incorporation of prosumer models based on waste heat recovery enables energy cascade utilization and enhances the system energy efficiency of DC-IES, and relevant technological pathways are depicted in Figure 7. In a broader context, as shown in Table 3, these technologies can be categorized into three pathways including thermo-electric conversion, thermo-thermal conversion, and thermo-cooling conversion.

In the context of converting thermal energy into electrical energy, low-temperature power generation technologies like ORC have emerged as a promising solution.¹¹¹ ORC employs organic working fluids with lower boiling points than water, enabling it to operate at low temperatures in comparison to conventional steam-based power plants.^{112,113} However, based on the theory of thermodynamic cycles, the efficiency of ORC driven by low-temperature waste heat in DCs is relatively limited, even below 5%.^{114,115} Consequently, some scholars have proposed integrating solar thermal collection and heat pump into DC to enhance the waste heat temperature or employing ORC to recover higher-temperature waste heat from devices such as internal combustion engines and hydrogen fuel cells in DC-IES.^{116,117} The effectiveness of ORC systems in utilizing waste heat from DCs was evaluated by considering both thermodynamic and economic perspectives,¹¹⁶ where R134a and R245fa as optimal choices for ORC. Moreover, a study was conducted on a heat pump-assisted ORC (HPA-ORC) system to recover waste heat from DCs.¹¹⁷ The findings indicated that the HPA-ORC system is up to 65% less expensive than air-source heat pump cooling systems, and its profitability increased with higher server utilization ratio.

In addition to its potential for providing district heating, the utilization of low-temperature waste heat generated by DC-IES has several other advantages

decrease for residential areas. Also, the feasibility of using a heat pump instead of mechanical cooling in DC was studied, to provide heating for an adjacent office building with an area of 416 m².¹²² A waste heat recovery project within a DC located on campus of Spain led to potential thermal energy savings of more than 254,106 kWh/year.¹²³ The Amazon DC in Dublin will begin supplying heat before the end of next year, providing heat to 47,000 m² of public-sector buildings, 3,000 m² of commercial office space, and 135 apartments by 2024.¹²⁴

Additionally, waste heat can be used to provide the necessary cooling energy for DCs through advanced technologies like absorption and adsorption refrigeration systems. When employing absorption refrigeration, different modes such as single-effect and double-effect can be chosen based on the temperature of the waste heat, resulting in varying COP for the refrigeration cycle under each mode. It is noteworthy that absorption refrigeration in DCs typically exhibits a COP below 1.0,¹²⁵⁻¹²⁷ rendering it less efficient compared to the heat pump. Therefore, its suitability for DCs relies on striking a balance between cooling costs and external heating prices.^{128,129} A performance analysis of lithium bromide-water and water-ammonia absorption refrigeration systems was conducted,¹³⁰ and it reveals that system performance is significantly influenced by waste heat quality, server coolant type, solution concentration, evaporator temperature, and operating pressure. A silica gel-water adsorption chiller unit, using silica gel as the adsorbent material to extract waste heat from the liquid-cooled server racks was employed.¹³¹ The results indicate that this refrigeration approach could improve energy efficiency by 22.5% compared to a baseline infrastructure without waste heat utilization. A model of a LiBr/H₂O absorption cooling system based on an enhanced geothermal system using concentric circle wells for DCs was established and verified.¹³² The cooling capacity of this system could reach above 9 MW with COP above 1.0 for providing cold water to DCs. An adsorption refrigeration system driven by solar and DC waste heat utilization was conducted,¹³³ and revealed that the application of DC waste heat recovery holds a promising economic prospect with a COP of 0.48. With the development of liquid cooling on DC, some experimental research is also exploring engineering demonstrations of adsorption refrigeration technology driven by waste heat directly from IT server racks.¹³⁴

Table 3. Summary of research on the interaction between computing network and heating network

Ref.	Utilization methods	Purpose	Location and temperature of waste heat recovery	Operating working fluid	Waste heat recovery performance
32	ORC-ABS	Power generation, cooling,	-	R123, LiBr-H ₂ O	η =14.45%(R123), COP=1.31
45	ABS	Cooling	Chips(30°C)	LiBr-H ₂ O	COP=0.69-0.71
46	ADS	Cooling	-(25°C-30°C)	Silica gel-H ₂ O	COP=0.2-0.6
48	ABS	Cooling	-	-	COP=0.8
64	HP	Cooling/ Heating	Return water	R450a, R513a, R515a, R515b, R516a, R152a, R444a, R1234ze, R1234yf, R290, R1243zf, R134a	COP=3.7-4.7 (R515b, heating), 2.7-3.6 (R515b, cooling)
75	CO ₂ HP	District heating	IT room chilled water (24°C); Water-cooled chiller cooling water (39°C)	CO ₂	COP=3.92(Water supply temperature 50°C)/ 3.17(Water supply temperature 70°C)
116	HP-ORC	Power generation	Micro evaporator on chip(60°C)	R134a, R245fa, R1234ze	η =4.7%
121	WSHP	Residential heating	CRAH return air	R-410a	COP=2.23(Cooling), 3.27(Heating)
122	ASHP	Cooling/ Heating	CRAC return air (25°C-30°C)	R134a, R410a, R404a, R407c	COP=3.95-5.45 (R134a, 298K-303K)
130	ABS	Cooling	-(60°C-120°C)	R245fa, R245ca, Water-ammonia, LiBr-H ₂ O	COP=0.62-0.85
131	ADS	Cooling	Server exhausts (40°C-65°C)	Silica gel-H ₂ O	-
132	ABS based on enhanced geothermal system	Cooling	Geothermal energy (150°C)	LiBr-H ₂ O	COP>1
133	ADS	Cooling	Waste hot water(50°C-60°C)	Silica gel-H ₂ O	COP=0.48
166	HP	District heating	Chilled water (18°C)	-	-
167	ASHP	Cooling/ Heating	CRAH return air	-	-
168	WSHP	Cooling/ Heating	Cooling water	-	COP=3(Heating), 4.5(Cooling)
169	Water to water HP	Cooling/ Heating	Return water (16°C)	-	COP=4.3
170	CO ₂ GSHP	Cooling/ Heating	Cabinet interior	CO ₂	COP=4.01
171	HP	District heating	-	-	COP=3.0-6.3
172	WSHP	District heating	-	-	COP=2.5-4.0
173	ORC	Power generation	Two-phase evaporative cooling system (100°C)	HFC-245fa	η =12%
174	CO ₂ HP-ABS	Cooling	Cooling return water(20°C)	R600a/R601a, R134a, R1234yf, R152a, R1233zd, R1234ze, R236ea	COP=2.12(R600a/R601a)
175	ABS	Cooling	Saturated vapor	R245fa, LiBr-H ₂ O	COP=0.82
176	ABS based HP	Cooling	Chips(90°C)	LiBr-H ₂ O	COP=0.87
177	ABS	Cooling	Chips	Water-ammonia	COP=0.73
178	CO ₂ power cycle CO ₂ refrigeration cycle	Cooling, power generation	Chilled return water(20°C)	CO ₂	COP=3.31
179	Water-cooled integrated air conditioner with thermosyphon	Heating/ Cooling	-	-	COP=20.4

Abbreviations: ABS, Absorption Refrigeration; ADS, Adsorption Refrigeration; ASHP, Air Source Heat Pump; CRAC, Computer Room Air Conditioning; CRAH, Computer Room Air Handler; HP, Heat Pump; ORC, Organic Rankine Cycle; WSHP, Water Source Heat Pump

Challenges and recommendations for future perspectives

Everything has two sides, especially when it comes to DC-IES, involving multiple subjects, covering a wide range, containing numerous variables, and exhibiting strong interconnections. Concerning the interaction between computing networks and power grids, current models around flexible DR

encounter several issues in DC-IES: (1) The economic benefits of DC-IES participating in grid interaction within the existing auxiliary service market are not prominent.¹³⁵ Given the current conditions of the spot market, the potential gains from integrating computing networks with power grids driven by ancillary service value are limited, which fails to elicit a proactive response

from DC operators.¹³⁶ For instance, the current pricing for frequency regulation in China sets a high threshold for large capacity entry, with peak-to-valley price differences across provinces only ranging approximately at 0.15 \$/kWh, and the peak-to-valley time ratio is relatively short (4 hours per day). To achieve higher returns, it is necessary to increase battery capacity or extend workload transfer over longer periods in DCs, and it affects the reliability of DC operations inevitably; (2) The second challenge lies in stringent data barriers that exist in the direct interaction between information flow and energy flow during the interactive process.¹³⁷ To facilitate the interaction between computing networks and power grids, it is necessary to possess comprehensive knowledge of the relationship between energy consumption and load curves of DCs, as well as the dynamic electrical characteristics of regional power grids, trends in spot markets, and energy prices.¹³⁸ However, the data involved in these instances may involve sensitive information about business finances, data transactions, and customer privacy of DC operators and their service clients. Consequently, it is imperative to establish a robust mechanism and approach for safeguarding and governing these exchanges between computing networks and power grids to ensure privacy security; (3) There is an inherent contradiction between computing power and electricity supply when it comes to providing high-quality services.^{139,140} Ensuring data integrity becomes crucial, especially when transferring workloads in third-party leased facilities. The interaction between computing networks and power grids inevitably consumes critical backup resources such as information storage capacity, network infrastructure bandwidth, and energy reserve capacity. This can increase the difficulty of task processing and the risk of rack failures in extreme cases.

As for the interaction between computing and the heating network in DC-IES, the challenges are considered as follows: (1) The cost-effective utilization of ORC driven by low-temperature waste heat from DCs poses a challenge in the context of DC-IES. The efficiency at such temperatures is below 5.0% (details can be found in Appendix Table 3), and installation investment for ORC exceeds \$1000/kW.^{141,142} Therefore, despite some research efforts focusing on working fluid selection and structural enhancements to improve performance, a viable business model solely relying on waste heat from DCs remains unfeasible unless innovative technologies such as solar heating and diesel generator exhaust are relied upon; (2) Although water source heat pumps driven by DCs waste heat show higher COP compared to air source heat pumps, many large-scale DCs are located tens of kilometers away from heating loads, which requires additional investment in heating pipe networks. Therefore, many DC-IES heating projects are small-scale and locally based, serving users such as office buildings or nearby residents.¹⁴³ However, the development of the DC-IES model may further highlight the potential for load interaction between DCs and its surrounding industrial parks, utilizing high-temperature heat pumps to generate steam from DC-IES for industrial production;¹⁴⁴ and (3) Advancements of absorption and adsorption refrigeration technologies present opportunities for self-cooling driven by waste heat in DC-IES. While this approach enables the utilization of free waste heat to cool critical equipment in DCs, the lower COP below 1.0 indicates that the waste heat generated by the IT server is insufficient to meet the cooling requirements of other devices, necessitating supplementation from conventional electric cooling systems. Additionally, the lower COP value also implies that absorption refrigeration units will dissipate more heat, thereby increasing the pressure on water resource consumption in DC-IES and impacting overall WUE in these facilities.

The challenges serve as the impetus for the collaborative optimization of DC-IES in research. From a theoretical and technical standpoint, current research focuses on various time scales of cooling, heating, electricity generation, and computing power through general system modeling and solving techniques.¹⁴⁵ Additionally, planning techniques for multi-stakeholder games within the system, optimal control of systems under computational task uncertainties,¹⁴⁶ multidimensional and multi-objective evaluation methods encompassing energy, economy, environment, and safety aspects of the system are explored.¹⁴⁷ Furthermore, secure governance of data under interactive modes of the system as well as risk control techniques are also addressed.¹⁴⁸ In the context of DC-IES, which synergistically integrates computing, power, and heating, this paper emphasizes one of the crucial aspects of accurate measurement and control of refrigeration systems with

thermal characteristics. These prerequisites are essential for facilitating the interaction between computing networks and power grids and cooling networks within the DC-IES, directly impacting its safe operation and exploration of interactive potential.^{149,150} Compared to traditional load balancing approaches, scenarios involving load transfer considering the interplay between computing networks and power grids necessitate faster and more responsive capabilities from refrigeration systems. While we acknowledge that the interaction between computing networks and power grids can be completed within milliseconds, energy consumption resulting from computing transfer along with associated heat dissipation processes in refrigeration typically exhibits slower time constants often measured in minutes. The inertia effects and constraints imposed by refrigeration systems have been largely overlooked or neglected in existing research, resulting in inadequate consideration of this boundary condition.¹⁵¹ The theoretically determined safe operating temperature range for IT equipment in DCs is influenced by both a model representing heat generation characteristics of IT equipment as well as a model describing the heat absorption capabilities of cooling systems. Consequently, some studies have focused on high-intensity computing while also delving into more intricate mechanisms governing heat generation in IT systems alongside advanced cooling technologies such as pump-driven two-phase cooling,¹⁵² heat pipes,¹⁵³ or immersion liquid cooling methods have been explored accordingly. The simultaneous integration of refrigeration systems, and heating networks with thermal storage devices, while comprehensively considering task transfer scales and device limitations, merits further investigation.^{154,155}

CONCLUSIONS

DC-IES demonstrates the enormous coupling and synergistic potential between the DC computing network and power grid, primarily from renewable sources, as well as the heating network using a heat recovery model. This paper provides a comprehensive review of the energy research on DC-IES in recent years from various aspects and elaborates on its generalization, approaches, methods, techniques, and future perspectives. The main conclusions of this paper are as follows:

(1) The field of DC-IES is undergoing rapid development in both research and practice, yet it remains in its nascent stages due to its inherent complexity. Its primary objectives encompass the promotion of renewable energy utilization, enhancement of energy efficiency, and exploration of untapped flexible resources. Ongoing research on DC-IES encompasses system planning, configuration design, operational evaluation, and problem-solving while considering emerging factors such as uncertainty associated with renewable energy sources, waste heat recovery, interactions with the power grid, and the impact of DR. The integration of generation-grid-load-storage technologies is gradually emerging as a crucial approach for DC-IES to actively participate in the new energy system which is characterized by renewable energy and waste heat recovery.

(2) The innovative DC-IES mode of flexible interaction between computing networks, power grids, and heating networks will unlock the immense potential of DCs to contribute to building a new energy system. However, when it comes to the interaction between computing networks and power grids, the current business models centered around flexible DR face several challenges. To ensure high security and reliability, we propose implementing distributed deployment of computing capacity across rack servers, establishing linkages between IT equipment and auxiliary systems, defining rules for flexible resource participation in the electricity market, as well as refining the contribution rules of interests' game when DC-IES involves multiple entities, electricity markets, and computing network business.

(3) In the context of computing networks and heating networks interaction in DC-IES, compared to the low thermodynamic efficiency and limited economic benefit of ORC conversion technology for waste heat recovery in DC-IES, compression heat pumps with high COP and absorption refrigeration technologies with self-cooling can effectively harness waste heat from DCs while generating positive technological and economic impacts. However, there are still some challenges including low customer acceptance, distance from end-users, seasonal heat demand, and IT equipment reliability. The economic viability of these two technological paths still requires a sophisticated calculation model for a comprehensive evaluation, particularly involv-

ing in-depth analysis of the payback period under varying external temperature and humidity conditions as well as internal utilization ratios.

(4) While the PUE indicator is crucial for evaluating the efficiency and cost-effectiveness of DCs, relying solely on it to assess the sustainability of DC-IES would be insufficient. To ensure sustainable operation, a comprehensive approach such as an analytic hierarchy process or multi-objective optimization should be adopted, considering unique integration between computing networks, power grids, and heating networks. This approach should encompass overall energy efficiency, utilization of renewable sources, waste heat recovery from DC operations, economic feasibility, and environmental sustainability measures while also considering reliability. Unlike IES evaluation characteristics, unique aspects of DC-IES must also be explored to accurately describe benefits in terms of improving rack server utilization ratio, accommodating renewable energy consumption and optimizing electric-thermal coupling efficiency.

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AUTHOR CONTRIBUTIONS

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DECLARATION OF INTERESTS

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