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Distributed Collaborative Optimal Scheduling of Regional Integrated Energy Systems with Multi-agent Participation

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Abstract. In response to the global transition toward carbon neutrality, Regional Integrated Energy Systems (RIES) have emerged as a critical technical pathway for multi-energy synergy. This paper provides a comprehensive review of the collaborative optimal scheduling of RIES, structured across four dimensions. First, we establish the physical modeling foundation based on the bus method, characterizing the deep coupling of electricity, heat, and gas flows, with a specific focus on the thermodynamic constraints of Compressed Air Energy Storage (CAES) and the flexibility of demand response. Second, we analyze the distributed hierarchical architectures, evaluating how Analytical Target Cascading (ATC) and game theory resolve the inherent conflict between global efficiency and stakeholder privacy. Third, we review the algorithmic evolution of swarm intelligence—such as PSO, GWO, and BOA—specifically focusing on chaos mapping and adaptive mutation mechanisms used to navigate non-linear constraints. Finally, we examine uncertainty mitigation strategies, synthesizing multi-time-scale coordination and robust optimization as key tools for hedging against source-load fluctuations. By identifying current research gaps, this review outlines a future roadmap toward digital-twin integration and system resilience, providing a strategic reference for modern energy interconnections.

Keywords: Regional Integrated Energy System, Enhanced Swarm Intelligence, Uncertainty Mitigation

1. Introduction

Accelerated worldwide industrialization and huge amounts of fossil fuel consumption have resulted in severe climatic changes and environmental pollution. Excessive green house gas emissions especially carbon dioxide is a global problem. Consequently, China has put forward the strategic goals of "carbon peak" and "carbon neutrality". This background drives a profound transition towards low-carbon and clean energy structure, so it is very necessary to raise the proportion of renewable energy, such as solar energy and wind energy, in the terminal consumption field. However, the inherent stochastic and volatile nature of renewables is challenging the stability of current power systems.

In conventional models of energy supply, electricity, heat supply and natural gas systems are generally separately planned and operated. This fragmented architecture has no synergy between different energy carriers, which constrains clean energy integration and leads to low energy cascade efficiency. For example, waste heat from thermal units often gets disposed away because there is lack of conversion pathways and renewable energy is often curtailed during peak times because of lack of system flexibility.

Regional Integrated Energy Systems (RIES) have been drawing considerable attention from the academic and technical communities recently as an important means of technical solution for efficient energy utilization. By combining co-generation units, energy conversion devices and storage systems, RIES enables the deep coupling and coordinated optimization of multi-energy flows. It's significance is reflected in three aspects as primary. First, multi-energy complementarity enables the system to leverage the conversion flexibility to buffer the uncertainty in the renewable outputs, to substantially enhance utilization rates. Second, energy cascade utilization in a region lowers the operating costs becoming economic benefits and environmental benefits. Finally for multiple-stakeholder environments (including microgrid operators and load aggregators), distributed scheduling allows for the protection of control rights and data privacy: essential for the development of secure and transparent energy markets.

Current research is based on four main areas. With respect to modeling and basic scheduling, researchers are interested in enhancing the accuracy of multi energy flow coupling. An optimization model was set up for multi-source microgrid through the improved chaotic particle swarm algorithm and proved the effectiveness of coordination in terms of reducing cost [1]. The potential of Power-to-Gas (P2G) and Vehicle-to-Grid (V2G) technologies associated in mitigating wind curtailment has also been analyzed [2]. Other studies had explored multi-objective scheduling strategies based on a three bus model [3]. For particular equipment a multi-time-scale scheduling scheme was proposed taking into account ramping capability of compressed air energy storage [4]. Additionally, intelligent scheduling for the distribution networks was researched for better compatibility of distributed generation [5].

In terms of multi-agent coordination and distributed architecture, distributed control has become the mainstream tool in order to protect the privacy of participants. A hierarchical autonomous optimization technique for microgrid clusters was proposed based on Analytical Target Cascading (ATC) [6]. Energy mutual assistance mechanism between sub-regions was studied to reduce the dependency on the external grid [7]. A double decoupling distributed algorithm of Crisscross Optimization (CSO) was further introduced to decrease the computational dimensions [8]. Other research used the non-synchronicity of the regional loads for resource optimization [9]. Furthermore, communication delays and fault tolerance in edge computing for real-time control was analysed [10]. Game theory has also been used to balance the interests of the operators and users under price incentives [11].

With regard to swarm intelligence algorithms improvement, scholars have optimized heuristic algorithms in order to deal with non-convex and non-linear features. An improved version of the Butterfly Optimization Algorithm (BOA) was applied to solve the premature convergence in microgrid cluster scheduling [12]. An enhanced Grey Wolf Optimizer (GWO) algorithm was used for the optimization of Pareto front of economy and carbon emissions [13]. For particle swarm optimization, a quantum mechanism has been introduced to enhance the accuracy of the search [14] and adaptive weights were involved to increase the robustness [15]. For larger variables, the excellent effect of the CSO algorithm in multi-regional coordination was confirmed, and computation has been helpful for the real-time scheduling [16]. In forecasting and risk management, source-load fluctuations management is important. Swarm intelligence has been applied to enhance the accuracy of load forecasting [17]. To cope with the prediction errors, a two-stage robust optimization model was presented for increasing the system resilience by worst-case scenario

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analysis [18]. Finally, a coordinated control strategy by making use of power regulation margins was designed for stable operation under extreme disturbances [19].

On the whole, the achievements in multi-energy modelling and intelligent algorithms are quite remarkable in the existing research. However, balancing the scheduling efficiency, information privacy and source-load uncertainty in multi-stakeholder environments is an important issue.

This paper focuses on the question of collaborative optimal scheduling of RIES in a multi-stakeholder participation. The core content include physical modeling of multi-energy flows based on bus method, distributed hierarchical scheduling framework based on ATC and game theory, improved swarm intelligence algorithms for non-linear constraints and multi-time-scale risk control strategies for source-load uncertainty. The goal of the effort is to balance between economic efficiency, physical security, and stakeholder privacy.

Chapter 1 develops on the research relevance of RIES in the context of the "dual carbon" goals and summarizes the current state of research in the areas of multi-energy flow modeling, distributed architectures, intelligent algorithms and uncertainty management. Chapter 2 sets up balance models for electricity, heat and gas buses, by analyzing the ramping limitations of compressed air energy storage (CAES), and "virtual storage" properties of demand response. Chapter 3 proposes an ATC-based hierarchical autonomous framework to integrate privacy protection, improved swarm intelligence algorithms to make better solving capabilities under complex constraints and multi-time-scale strategies to mitigate the prediction error. Chapter 4 restates the economic and security importance of distributed collaborative scheduling but emphasizes that future studies need to be devoted to improving the combination of data-driven approaches with physical models and enhancing the resilience of the system.

2. Analysis of RIES

Following the background and significance of RIES discussed in Chapter 1, a deep exploration of their physical composition and operational mechanisms is the logical starting point for constructing optimization strategies. This chapter first provides a more detailed description of the RIES system architecture and interconnection topology and analyzes the benefits of energy utilization in a cascaded system and the possibility of mutual resource aid in multi-regional interconnections. Subsequently, mathematical models for core equipment, including gas turbines, boilers, and Compressed Air Energy Storage (CAES), are discussed. Finally, energy flow balance criteria are analyzed, alongside the challenges of interest games and privacy protection in multi-agent distributed scheduling. The physical models and mechanism analysis established in this chapter provide the theoretical foundation for designing distributed scheduling algorithms [20].

2.1. Architecture

The term RIES is the fundamental physical representation of the modern Energy Internet, at the regional level. It is not just a physical system of convergence of heterogeneous energy flows like electricity, heat, cooling, and gas, it is a high-level system of integration of energy, information, and value flows achieved through the coupling, conversion, storage, and communication technologies. RIES breaks the traditional "island mode" of independent planning and operation, and establishes coupling links between different media in order to greatly improve the energy cascade efficiency. Against the backdrop of energy transition and "dual carbon" goals, RIES is a very important platform to integrate high proportions of renewable energy, reduce the carbon intensity of the region and improve the energy system's resilience.

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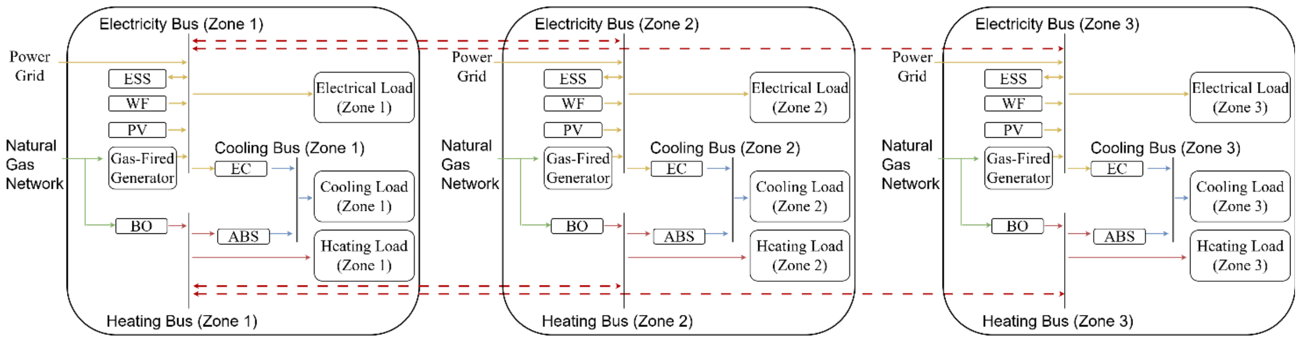

Figure 1. Structure of RIES

A typical one region RIES is the smallest unit of physical size for multi-energy complementarity. As can be seen in Figure 1 the internal architecture is focused on the Electricity Bus, Cooling Bus and Heating Bus. This bus-based decoupling approach reduces sophisticated mesh energy flows to nodal power balance logic. At the input layer; the system receives fossil fuels and supports from the grid through the external power grid and natural gas grid. Distributed power sources are predominantly wind farms (WF), photovoltaics (PV) with a high degree of volatility and stochasticity. To reduce this uncertainty, gas generators (GEN) are regarded as fundamental "electricity-heat" coupling terminals, in the sense that, to produce high-quality electricity on the electricity bus, they consume natural gas, and simultaneously transfer exhaust heat to the heating bus via heat exchangers. Gas-fired boilers (BO) are used as pure heat sources to maintain thermal stability at times of demand surges or heat shortages. The conversion and cooling logic provide great system flexibility. Electric chillers (EC) use electricity as input and cooling as the output by means of the reverse Carnot cycle whereas absorption chillers (ABS) use low-grade thermal energy input for refrigeration. This dual "electricity-cooling" and "heat-cooling" pathway allows for physical load shifting during peak time periods. In addition, energy storage systems (ESS) are used to act as flexible buffers on the electricity bus, to facilitate the integration of renewable energy through time-shifting of energy. Ultimately, all the energy that is converted and stored is used to meet the terminal electrical, cooling and heating loads.

Establishing a multi-region integrated energy system (M-RIES) enables global resource optimization by taking advantage of the "non-synchronicity" of energy consumption habits and resource endowments of industrial, commercial, and residential zones. As shown in Figure 1, the model in this paper covers the Zone 1, Zone 2 and Zone 3. These sub-systems eliminate administrative and geographical boundaries using physical tie lines and tie pipelines and create a tight electricity-heat interconnection. In this architecture, each regional Energy Management System (EMS) is responsible for the balance at the local level and take part in the inter-regional energy trading. For example, PV surplus in Zone 1 can be transported to the load center in Zone 2 using tie lines to prevent curtailment; in case of a heat surplus from Zone 3, the heat can be transported to residential areas for heat purposes. The key to this mechanism is mutual benefit, to reduce the impact on external grids at an instantaneous level and to lower the total costs by using the complementarity of loads. To promote cooperation instead of competition, research often involves using methods of cooperative game theory such as Nash bargaining or Shapley value techniques to make sure that the surplus gains are shared in a fair manner and the system is stable.

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2.2. Equipment modeling

Precise modeling of the core equipment is a prerequisite for the engineering feasibility of the scheduling strategies. This section examines the development of the modeling logic for different conversion and storage devices.

In terms of production equipment, the characterization of the efficiency of gas generators (GEN) and gas boilers (BO) has gone from taking constant values to representing dynamic non-linear models. The power generation efficiency of a GEN varies widely with fluctuations in load rate under part load conditions and therefore variable efficiency curves are needed for a refined analysis. In the cooling and heating sector, the modelling of electric chillers (EC) and absorption chillers (ABS) is based on the coupling analysis of their Coefficient of Performance (COP). Although, the instantaneous COP of an EC will be higher the instantaneous (ABS) might provide better integrated economy when thermal energy is abundant. This life-cycle efficiency analysis is in favor of decision-making in switching between cooling pathways during summer peak loads.

As a special form of storage technology, Compressed Air Energy Storage, abbreviated CAES, has the following thermodynamic characteristics: CAES differs in detail from electrochemical storage. During the compression stage, electric energy is transferred into the internal energy of a high-pressure air. The air cavern model needs to consider the leakage rates and pressure losses during the storage. In the expansion stage the high pressure air is used to drive a turbine to generate electricity. The main modelling issue is ramping constraints. Due to the rotational inertia of the compressor and turbine and temperature field constraints, there are physical limitations of power adjusting speeds. Ignoring these constraints can result in "logically correct but physically infeasible" solutions on fast fluctuations in renewable output. Therefore, a quasi-steady-state CAES model with ramping limits is indispensable to guaranteeing the security of grid frequencies and stability of multi-region grids.

Load-side modeling is changing from "rigid demand" to "flexible resources." By taking the concept of elasticity matrices from microeconomics, terminal demand is categorized under fixed, shiftable and curtailable loads. The main logic behind this is the characterization of user feedback in the form of Price-based Demand Response (PDR) or Incentive-based Demand Response (IDR). This effectively reduces terminal demand to "virtual storage" or "shadow units." For example, encouraging industrial users to redistribute their production at peak time through tiered pricing is the same thing as running a reserve unit. Multi-regional demand response should also take into account different response motivations across different zones. Flexible load models therefore considerably extend the margins of regulation and reduce renewable integration pressure (without further hardware investment).

2.3. Energy balance and game mechanisms

The stability of RIES is based on the instantaneous or quasi-steady state balance of the electricity, heat and cooling buses. Electricity bus balance contains external purchases, renewable, and unit output and tie line power. Thermal and cooling systems are differently heterogeneous. Thermal energy flow has a large delay and inertia in the transmission of the pipe network and heat exchange in the building. Consequently, the bus heating does not need to be absolutely second by second balanced, but ensures energy preservation in a given time interval instead. The thermal network can be seen as a quasi-storage system, which preheats in the low demand times and releases the heat at the peak times providing "temporal decoupling" from the electrical regulation. This inertia-based modeling opens the feasible region in electro-thermal optimization and is essential for maximizing multi-energy complementarity.

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Market reforms in M-RIES architecture have the sub-regions often belonging to different investors or operators. This is a multi-agent context that challenges scheduling to shift from centralised control towards "hierarchical autonomy and collaborative operation." The first difficulty is interest conflicts and game equilibrium. As rational economic agents, regional operators seek to keep down their own operating costs, fuel costs and carbon costs as far as possible. Independent optimization can often lead to Pareto inefficient states where individual optima lead to poor global performance. For example, Zone A may give up tie-line capacity to save itself money, so that Zone B is prevented from exporting clean energy. These conflict situations require the use of game theory which may be in the form of non-cooperative or Stackelberg games for a Nash equilibrium to be achieved. The second challenge has to do with distributed scheduling and the privacy boundaries. In competitive environments, internal data, such as accurate unit efficiencies, real-time load forecasts and bidding strategies, are sensitive commercial secrets. Centralized scheduling requires uploading of all detailed data that in practice is difficult. Therefore, distributed scheduling is the ideal option. This framework provides strong information boundaries with regional EMSs only exchanging "coupling variables" such as tie-line power and nodal prices and keeping internal modeling information encapsulated. This "local logic, private data" mechanism makes decision-making less computationally intensive and preserves the sovereignty of decision-making for each agent.

3. Distributed scheduling

Following the definition of the RIES physical architecture and fundamental equipment modeling, the optimal energy allocation under the participation of multi-stakeholders through efficient mathematical methods has become one of the central research areas. Given the complex characteristics of RIES (including heterogeneous energy flow coupling, multi-stakeholder game, and strong source-load stochasticity), the traditional centralized scheduling schemes exhibit very obvious limitations in some aspects of computational efficiency, communication overhead, and privacy protection. This chapter focuses on mathematical decoupling mechanisms of distributed scheduling frameworks, optimization logic of swarm intelligence algorithms and multi-time scale risk management strategies for source-load uncertainty.

3.1. Hierarchical scheduling

In an M-RIES environment with different regions and investors, sub-regions often exist with different operators that have different interests and strict data privacy requirements. The fundamental mission of a distributed scheduling framework is to direct the globe system to a Pareto optimal resolution by mathematical decoupling without entry to the fundamental internal data for the several stakeholders.

For vertical relationship of regional energy center (higher level entity) and subject to subordinate multi-energy microgrid clusters (lower level entities) ATC provides a serious hierarchical decoupling paradigm. Mathematically, ATC builds the global optimization problem as a nested bi-level optimization model. The global economy and tie-line power stability is the upper-level regional center that issues the expected boundary interaction target, for example, electricity and heat power values. Post-receipt of these targets, lower-level microgrids are able to provide feedback on their actual optimal response power while meeting internal constraints such as gas turbines, energy storage and flexible loads.

The main benefit of ATC is that it uses exponential or second order Lagrangian penalty function terms. These terms strictly penalize the mismatch between upper and lower limits variables.

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Through alternating iterations, the two levels get physical consistency on boundary power. This mechanism has "logical centralized coordination" and "physical distributed computation". Internal parameters, load curves, and bidding strategies of the microgrids are all kept locally without having to worry about trust barriers between different stakeholders and are fully encapsulated. Furthermore, ATC has a good convergence robustness. Even in the case of complicated electro-thermal coupling constraints, the system can quickly converge to a Nash equilibrium by the dynamic adjustment of the penalty functions.

In the case of peer to peer interconnected scenarios (Zone to Zone), a simple hierarchical structure is not sufficient to describe complex inter-regional energy exchanges. Researchers have proposed a "double-decoupling distributed scheduling" architecture to decouple the regional coupling in the spatial dimension with the correlation in time. Spatially, every regional EMS captures the marginal energy cost (MCP) of tie lines using Lagrange multipliers. This abstracts the global coupling constraints to marginal terms in the local objective functions assuring the privacy boundary where "data remains local and logic is localized". Temporally the forward-backward substitution strategy or heuristic decomposition strategies break down long-term day-ahead plans into independent hourly optimization problems, greatly alleviating the dimensionality challenge in large scale integer programming. This architecture enables RIES to support "plug-and-play" functionality. When an industrial microgrid or commercial complex joins the system, instead of updating the global model, only the dual variable mappings of adjacent nodes, so the engineering scalability is greatly improved.

As RIES involves stakeholders at different levels like operators and load aggregators game theory is a great tool in balancing diverse demands. Stackelberg game models are commonly used to explain this asymmetric decision-making process: the upper level operator decides up and down electricity/heat prices as signals to steer demand response at lower level and how users respond in the turn back influences the upper-level pricing decisions. In order to avoid the global efficiency losses due to unilateral search of individual optima, researchers have put forward the Nash bargaining mechanism in the framework of a cooperative game. By the construction of a cooperative surplus distribution model that aims to maximize social welfare, excess benefits of mutual assistance are distributed in a fair way using the Shapley value or nucleolus method. This mechanism assures motivation of the stakeholders to participate in the coordination, which brings to the organization both mathematical convergence and economic feasibility to multi-agent scheduling.

3.2. Algorithm optimization

Traditional gradient-based exact solution methods, services as simplex method and interior point method, can often suffer from the search stagnation and dimensional explosion of non-linear thermal characteristics of gas turbines and discrete State of Charge (SOC) constraint and step function carbon trading mechanisms. Swarm intelligence algorithms owing to their heuristic search capabilities and parallel processing capabilities have become central to solving these non-convex and non-linear scheduling problems.

Particle Swarm Optimization (PSO) shows rapid convergence of the initial values in multi-source microgrid scheduling, but has the "premature convergence" fault that it tends to get trapped in local optima. To deal with this, researchers have worked to make improvements two-dimensionally. First, space ergodicity of search space is improved by using Chaos Mapping (Logistic mapping, Tent mapping etc.) to replace pseudo-random initialization. The non-periodic and regular nature of chaotic sequences guarantees that the initial population is uniformly spread throughout the huge decision space, so that search dead ends are effectively avoided.

Secondly, search operator goes through the dynamic evolution by asynchronous learning factors and non-linearly decreasing inertia weights. In early stage, the ewning perturbations in individual and coluviel experience escalates the "exploration" ability of particles to "find" optimal regions over the whole globe. In later stages, the weights have been compressed by sine or exponential functions in order to introduce more "exploitation" for refined local searching. To manage complex constraints in RIES, a dynamic penalty function-based strategy is proposed aimed at guiding the population toward the feasible region by assigning the population solutions in the incomprehensible region high prices if they violate physical constraints. Experimental data show that the developed improved chaotic PSO can enhance the optimization accuracy of more than 12% compared to the standard PSO in multi-objective models with tiered carbon trading, which can greatly reduce total operating costs.

The Butterfly Optimization Algorithm (BOA) is a new algorithm for updating positions based on simulated dynamic change of the intensity of fragrance during the search for food resources. To deal with non-smooth solution spaces caused by fluctuations of source and load, researchers have introduced Cauchy Mutation and adaptive sensing factors in the BOA. The long-tail distribution of the Cauchy operator produces large-span jumps which allow the algorithm to escape local extrema.

Similarly, for multi-objective optimization of RIES, a better implementation of Grey Wolf Optimizer (GWO) imitates strict social hierarchy of wolf packs. By adding a leading wolf update strategy based on Euclidean distance, the Pareto front distribution is more accurately illustrated by the algorithm. For the RIEs models with P2G, V2G and various heat pumps, such better algorithms show good parameter stability and offer a series of compromise decisions that balance between the economic and environment goals.

For large-scale systems that have many decision variables, Crisscross Optimization (CSO) has advantages that are unique to this method. It uses "horizontal crossover" for information sharing between dimensions and by "vertical crossover" for the fine tuning of particle positions within one dimension. This dual mechanism is effective for the suppression of "dimensionality collapse" in high dimensional non-convex problems. Furthermore, by combining reinforcement learning such as Q-learning with CSO, it is possible to dynamically adjust the step and crossover probability from the historical data. This combination of data-driven and heuristic search reduces the computational time for intraday rolling scheduling substantially, which generates the power needed to support real-time control.

3.3. Uncertainty management

The main challenge in scheduling the RIEs is the huge stochasticity of renewables and the uncertainties of the behaviour of load. Deterministic scheduling is ineffective in many cases because of prediction errors and therefore creating an anti-risk intelligent scheduling system is a must.

To hedge against the exponential run up of prediction errors with time, multi-time scale coordinated scheduling is widely used. First, in the day-ahead stage (24h horizon, 1h step), long-term forecasts are used to optimize the charging/discharging of large-scale storage such as CAES and the unit commitment of slow response units such as gas turbines in order to minimize the daily costs. Second, in the intraday rolling stage (4h horizon, 15min step), still under the guidance of dynamic sliding window and deep learning (BiGRU or Attention mechanism), day-ahead plan is refined. This stage maximizes "dynamic power regulation margins" to stand in reserve in the face of wind power surges. Third, in the real-time correction stage (5min step) distributed consensus algorithms give commands to fast-response supercapacitors or flexible loads to micro-adjust power imbalances, ensuring bus voltage and frequency stability. This "layered refinement and dynamic game" logic allows for microscopic stability with macroscopic economy.

For the large deviations in predictions (due to extreme weather), Two-stage Robust Optimization offers an "optimal decision under the worst-case scenario." In the first stage (pre-decision), rigid decisions such as unit commitment under an uncertainty set are determined. In the second stage (adjustment), the system adjusts itself again for the worst wind and solar-case. This model is usually solved by the Column-and-Constraint Generation (C&CG) algorithm by a sequence of alternating iterations between a Master Problem and a Sub-problem. Although there is a resulting increase in operating cost through robust optimization ("conservatism cost"), this adds to the system's ability to survive extreme system disturbances, particularly when we look at hard constraints such as CAES ramping limits.

Alternatively there is Chance Constrained Programming where constraint violations are possible at very low probabilities (e.g. at 1%-5% confidence) in order to gain economy. By employing probability distribution functions, in order to characterize the error of predictions, stochastic constraints are converted into deterministic non-linear constraints. Furthermore, by combining edge computing with federated learning, it is possible for sub-regions to train a global prediction model without having to upload raw data. This "distributed data and collaborative evolution" model is used to improve prediction accuracy while respecting the privacy of the stakeholders.

3.4. Strategy evaluation

The effectiveness of the distributed algorithms and better swarm intelligence, discussed in this chapter, have to be evaluated in accordance with physical principles. First, real-time performance has to track the adjustment characteristics of the RIES. For example, the thermal inertia of heat networks is such that minute-level scheduling is possible but power grid balancing requires millisecond-level convergences. Distributed CSO algorithm discussed here leverages on the parallel computing, which greatly reduces the iteration time; intraday rolling requirements can be reached.

Second, the physical constraint compatibility is the "touchstone" for intelligent algorithms. Specifically, when taking into consideration non-linear CAE ramping and heat loss, the algorithm will need to return smooth and physically logical power curves. By placing dynamic handling of constraints, the enhanced algorithms make sure instructions are logically feasible as well as physically feasible (preventing the "power jumps" found in traditional algorithms).

Finally, economic guidance, under carbon trading, is proven to be effective. Through introducing a tiered carbon trading model, the smart algorithms can accurately reflect the marginal equilibrium between low carbon operation and generation costs. This direct the RIES to achieve emission targets through multi-energy complementarity - for instance, the use of P2G to convert curtailed wind to green hydrogen - reflecting the flexibility of the algorithms of dynamic multi-objective weighting.

4. Conclusion

In order to solve the collaborative scheduling problems currently encountered by RIES with the global energy transition, this paper developed a thorough exploration in three dimensions from improvement of physical modeling, game-theoretic system, and algorithmic mechanisms. Research suggests that RIES, or renewable, integrated, energy-saving systems, which breaks physical boundaries of traditional "islanded" energy systems. By deeply coupling the flows of electricity, heat, and gas and making better use through the cascaded utilization of flexible resources (such as compressed air energy storage), RIES provides a good way to increase renewable energy penetration and decrease the total system operating costs. In complex environments with multiple stakeholders, the distributed scheduling framework (with Analytical Target Cascading (ATC) and Lagrangian duality) is successfully used to provide a privacy boundary with "local data and localized logic". This creates a Nash equilibrium among competing interests and effectively addresses the dimensionality disaster and information security challenges of the centralized scheduling.

At the algorithmic level, this paper proves to be more superior improved swarm intelligence algorithms in dealing with the strong non-linear constraint of RIES and tiered carbon trading mechanisms. The introduction of chaos mapping and the adaptive mutation operator greatly enhances the escape trap of the local optima to ensure the economic efficiency and physical feasibility of the scheduling plans. Simultaneously, the combination of multi-time scale coordination strategies and effective optimization models constitutes sound risk hedging tools in the management of extreme uncertainties on both source and load sides. In sum, the construction of a distributed intelligent scheduling system based on physical accuracy, stakeholder sovereignty, and algorithmic robustness is the indispensable direction of low-carbon regional energy transformation and efficient operation.

Despite the milestone achievements in RIES research, there are a number of key areas that should be further explored while the Energy Internet progresses towards greater intelligence and transparency. First, the refined characterization of multi-energy flow dynamics is yet to be improved. Future studies should also take more into account the spatio-temporal distribution characteristics of thermal networks in long-distance transmission as well as the dynamic evolution of conversion equipment efficiency in complex situations, in order to solve the accuracy of scheduling instructions in millisecond-level frequency fluctuation.

Second, deep physics-informed data-driven modeling is a very important emerging trend. With the development of edge computing and federated learning, the most critical point for making the system more intelligent is to use vast multi-dimensional sensing data to adjust parameters in the physical model - thereby establishing the "cyber-physical" digital twin scheduling platforms - while keeping the privacy strictly protected. Furthermore, the creation of collaborative mechanisms for trading on the carbon, electricity, and gas markets needs to be studied in depth. Guided by "dual carbon" goals, researchers will need to examine how to deeply couple carbon emission rights, green certificates and energy trading in the temporal and spatial dimensions.

Finally, focus should be placed on system resilience assessment in the case of extreme disaster. Future research should not only be restricted to the conventional optimization of operation but should also address the topological self-healing and the islanded operation capabilities of the system in the event of extreme weather or communication link failures. Developing highly robust strategies for resilience enhancement will ensure both the absolute security and reliable supply of national energy infrastructure and meet "zero-carbon" targets at the same time.

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