

Carbon Neutral Energy Internet Intelligent Regulation Research Status and System Reconstruction

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Abstract:

Energy Internet is a key infrastructure to reach the goal of sustainable development through digital, intelligent, automated and networked technologies to reshape the realization of energy sources, grids, loads and storage, and is currently facing the key contradictions such as multi-energy flow synergy, carbon metering accuracy, and the transformation of control architecture. In this context, the analysis of technical bottlenecks as an entry point, combined with examples and research status innovatively proposed digital twin-driven architectural reconfiguration and new paradigm of quantum co-regulation system reconfiguration path, to ensure the coordinated conversion of multiple energy sources and energy allocation of the basic grid platform, aiming at the direction of the formation of the relevant industry chain in the future, and the system reconfiguration of the Internet of Energy under the goal of carbon neutrality to provide theoretical support and technical routes for reference.

Keywords:

Energy Internet, Carbon Footprint, Multi-energy Coupling, Digital Twin, Blockchain

1. Introduction

The global climate crisis and the future “carbon tax” policy pose a major challenge to the existing energy system, and it is urgent to promote the transformation of the energy system to low-carbon and high-efficiency. According to the International Energy Agency (IEA), carbon emissions from the energy sector will account for 73% of the global total in 2022, and the decarbonization of the power grid will become the core of the carbon neutral strategy. Energy Internet is centered on electricity, reconfiguring the logic of traditional energy system operation, and promoting multi-energy complementarity and efficient allocation.

However, the architecture of the Energy Internet faces many technical challenges. Energy system barriers such as electricity, hydrogen, heat, etc. hinder multi-energy coupling, and spatial and temporal dynamic characteristics and system stability need to be guaranteed. In addition, carbon footprint accounting has problems such as

difficult traceability and lack of refined management, and the coordination contradiction between centralized and distributed control needs to be solved [1].

2. Current Research Status of Intelligent Regulation of Energy Internet

2.1. International research progress mapping analysis

Based on the bibliometric analysis of Web of Science (WOS) and Derwent Innovation Index (DII), the number of global research papers and patents on the Internet of Energy is growing rapidly, with China and the United States as the main contributors. China has surpassed the US in the number of papers since 2017 and continues to grow [2]. The research direction has shifted from power electronics to multi-energy coupling and intelligent deployment, and the applied research focuses on information transmission, data processing systems (e.g., smart microgrids) and energy trading platform development. Research hotspots in recent years include multi-energy complementarity, energy storage technology, energy market mechanism and user-side interaction [3,4].

Despite the active research, there is still room for improvement in the innovation and market conversion rate of basic research, indicating that further breakthroughs are needed in practical applications and commercialization.

2.2. Classification of key technology areas

The field of intelligent regulation of energy Internet presents three hot clusters including optimization of multi-energy coupling system, carbon metering and blockchain fusion technology, and distributed artificial intelligence control.

In terms of the optimal design of multi-energy flow systems, the research mainly focuses on the fusion application of mixed integer planning and deep reinforcement learning. Based on the modeling and solving of wind, light, water, electricity and other models, the effective integration of photovoltaic (pv), wind power, combined heat and power (CHP) and other distributed energy sources realizes the synergistic and graded utilization of multiple energies, significantly improves the efficiency of the use of clean energy, reduces the carbon emissions caused by the energy consumption, and promotes the construction and development of integrated energy sources [5].

In order to curb greenhouse gas emissions, achieve emission reduction targets, and adapt to the future trading environment, the concept of carbon trading has been formally proposed [6]. Carbon emissions from energy systems is an important indicator that affects the allocation of carbon emission allowances in each country, and it is necessary to measure and account for all types of specific energy systems, including multi-energy coupling systems, and effectively differentiate between regions at the management level, allocate carbon emission allowances for different countries, regions, and production sites, and count carbon emissions, and the use of blockchain technology will facilitate the construction of the Unified Global Carbon Exchange (UG-CET) system on this basis [7].

Distributed control methods can be applied to energy Internet device management with a wide range of application prospects, such as self-organizing multi-intelligence body systems, which can address the flexibility, accessibility, reliability requirements and economic requirements of the technology of smart grids that rely on distributed

generation and demand-side management. [8,9] Distributed AI framework is embodied in exploring the synergistic mechanism of federated learning and edge computing, which can effectively solve the problems of centralized AI scaled computing and insufficient datasets, and can be adapted to the complex application scenarios of the energy Internet, linking numerous computing devices and units. (Figure 1)

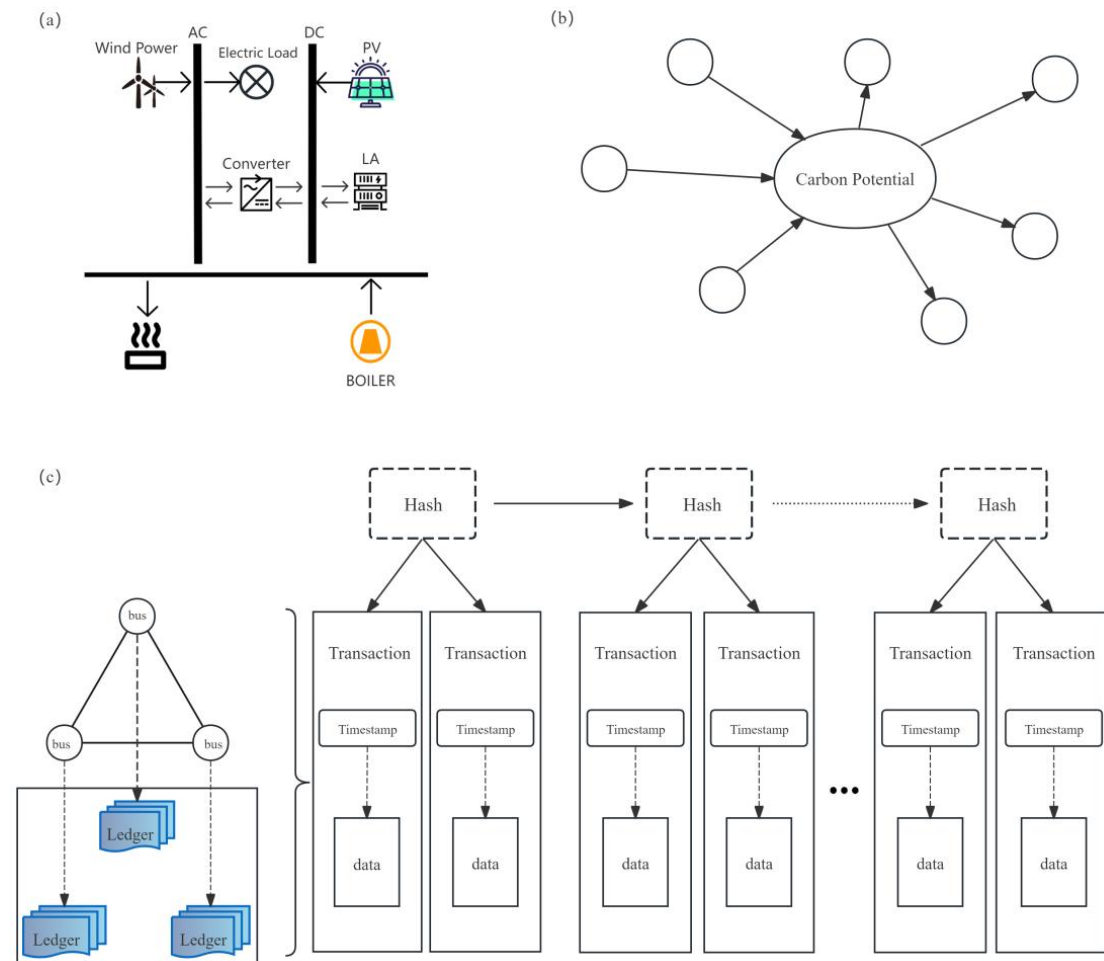


Figure 1. (a) Schematic diagram of a typical wind-photo-thermal multi-energy coupled system. (b) Schematic diagram of grid carbon flow. (c) Diagram of blockchain structure and operation.

2.3. Limitations of the current research paradigm

In the optimal design of multi-energy coupled systems, wind and photovoltaic power plants need to coordinate the scheduling models of wind turbines, photovoltaic arrays and energy storage plants. The volatility and unpredictability of wind and solar resources may lead to power fluctuations and threaten system security [10]. Prioritizing power generation gains may affect power quality and increase unit losses, while abandoning wind and light brings high penalty costs. Therefore, the system design needs to incorporate both day-ahead and intraday dispatch models. However, 78% of current dispatch models use hourly resolution, which makes it difficult to capture second-level fluctuations in wind and minute-level responses in hydrogen storage, and fails to meet the demand for 15-minute resolution, and model updating brings hidden costs [10].

For complex energy systems, accurate measurement of carbon emissions is key. The life cycle method and the carbon emission factor method are commonly used for calculations, but the lack of uniform standards for boundary delineation affects data accuracy and standardization, making it difficult to support the construction of carbon trading platforms. The average factor method has a high error rate (25%-40%), which further reduces data credibility [11]. In addition, the lack of a credible third-party audit mechanism makes it difficult to guarantee the authenticity of cross-border data, leading to a lack of trust in the carbon trading market and the formation of data islands. (Figure 2)

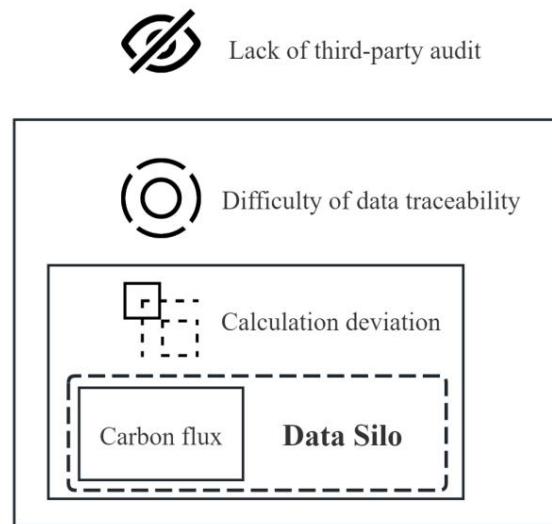


Figure 2. Principles of data silo formation in carbon market.

After the completion of multi-energy flow optimization design and blockchain carbon emission statistics, centralized data aggregation needs to be carried out through the Internet Data Center (IDC) to participate in microgrid demand-side response provisioning. This process relies on cloud interconnection and grid-level IoT convergence, and requires node task planning and allocation under massive time-varying information to reduce equipment redundancy. However, the computing platform requires strong data processing capability, and there is a contradiction between distributed node resource allocation and centralized control model. With the large-scale access of distributed photovoltaic and energy storage, the decision latency of centralized control at 100,000+ nodes grows exponentially, and the contradiction between centralized and distributed AI becomes increasingly prominent [12].

3. Review of Key Technologies and Bottlenecks

3.1. Electric-hydrogen-heat multi-energy flow dynamic game

3.1.1. Progress in multi-timescale coupled modeling

Scholars at home and abroad have made remarkable progress in modeling and solving multi-energy flow coupled systems. From the perspective of system structure, the multi-energy flow system can be regarded as the coordinated planning and combined solution of different energy subsystems; from the perspective of time scale, it involves multi-decision variables and equations, presenting nonlinear characteristics. For this reason, scholars introduced the second-order cone relaxation technique to relax the grid current constraints and transform it into a mixed integer planning

problem solution [13]; or used deep reinforcement learning algorithms (e.g., DDPG), which guides the cost minimization through a negative incentive mechanism to synthesize the scheduling cost, storage end-state restoration, and energy balance penalties under the premise of guaranteeing the generality and robustness.

Mixed integer dynamic programming is suitable for hourly scheduling. For example, in the hourly power demand validation in Saudi Arabia's Electricity Testing Laboratory, the AUGMECON2 algorithm was used to generate the Pareto optimal solution set, combined with the TOPSIS multi-criteria decision-making method to optimize the design of the hybrid PV-hydrogen storage system, and processed the 8760-hour time-series optimization problem through the CPLEX solver in the GAMS software to achieve the combination of daytime PV power generation and nighttime dynamic management of hydrogen storage and power supply [14]. However, the complexity of this algorithm is high, and although 95% of the day-ahead scheduling accuracy is achieved in the Enera project in Germany, the computational time consumed grows $O(n^3)$ with the increase of variables.

Table 1. Comparison of integer planning algorithms and deep reinforcement learning algorithms.

	Integer Programming Algorithms	Reinforcement Learning Algorithms
Core Principle	Based on mathematical optimization, models problems as Mixed Integer Linear Programming (MILP) and solves them using branch-and-bound or cutting-plane methods for global optimality	Relies on trial-and-error and reward mechanisms, interacting with the environment to learn policies. Uses deep neural networks to approximate policy functions without explicit mathematical models.
Applicable Scenarios	Static optimization problems with high certainty and explicit constraints.	Dynamic, uncertainty-heavy real-time optimization.
Computational Efficiency	Fast for small to medium-scale problems. Suffers from exponentially increasing complexity with problem size, requiring high-performance solvers.	Training phase is time-consuming, but single-step decisions are fast (~0.01 seconds), suitable for real-time control.
Model Accuracy	Provides globally optimal solutions with high precision but depends on accurate physical models and parameters.	Solution quality relies on reward function design and training data; may converge to local optima but generalizes well.
Interpretability	Transparent models with traceable decision processes.	Black-box models with opaque decision logic; post-hoc analysis tools are often needed.
Data Requirements	Requires complete system parameters and historical data; sensitive to data noise.	Depends on large interaction datasets but can generate data via simulations; less reliant on data completeness.
Integration Potential	Combines with RL for global planning (MILP) and local real-time optimization.	Integrates with digital twins for strategy validation and accelerated training via simulations.

Deep reinforcement learning algorithms excel in second response. As an example, the power-heat-hydrogen energy system is modeled by DDPG algorithm and set up the state space and action space to verify the system sustainability under typical day scenarios in winter. In 60 stochastic source load scenarios ($\pm 30\%$ fluctuation), the average scheduling cost of DDPG-LC and DDPG-LS is only about 5% away from the optimal solution of the dynamic programming (DP) theory, and the single-step decision-making time is only in the order of 0.01 sec, which demonstrates excellent real-time scheduling capability. However, the training stability of DDPG relies on

hyperparameter tuning and is prone to fall into local optimality, which limits its practical application. (Table 1)

3.1.2. Dimensional disaster problem of Nash equilibrium solving

According to domestic and foreign scholars' review of the algorithm of integrated energy system and the power market relationship, setting the energy Internet in the existence of non-cooperative game of multiple subjects, and strive to reduce costs and increase efficiency, energy saving and emission reduction, the ultimate goal is to solve the Nash equilibrium, and with the increase in the complexity of the system, it will be faced with dimensional catastrophe.

In the energy Internet, access to a large number of distributed resources (such as photovoltaic, electric vehicles, smart buildings) will lead to a surge in the number of participants, which is difficult to be handled by traditional optimization algorithms. On the user side of the electricity market, with the increase of user electricity consumption strategies, the surge in the dimension of the strategy space will make the computational task far beyond the limit of computing power.

3.2. Real-time Carbon Footprint Tracking Technology

3.2.1. Theory Development Lineage of Carbon Flow Calculation

Carbon flow is a virtual network flow that describes the greenhouse gas emissions in the fossil fuel combustion process. Currently, carbon flow calculation methods can be divided into two categories: macro scale includes IPCC standard, input-output (I-O) method and Kaya carbon emission equation; micro scale includes process life cycle assessment (LCA), hybrid life cycle method and carbon calculator and other techniques. Input-Output (IO) method, as a typical representative, is widely used in the power system. This method calculates carbon emissions by counting the consumption of various types of fossil energy and combining them with carbon emission factors. Its advantage lies in the simplicity of calculation and easy access to data, but there are significant limitations: the sectoral division is too loose, and it is impossible to realize the node-level carbon flow tracking and traceability, which seriously restricts its guiding value in the analysis of power system trends. (Figure 3)

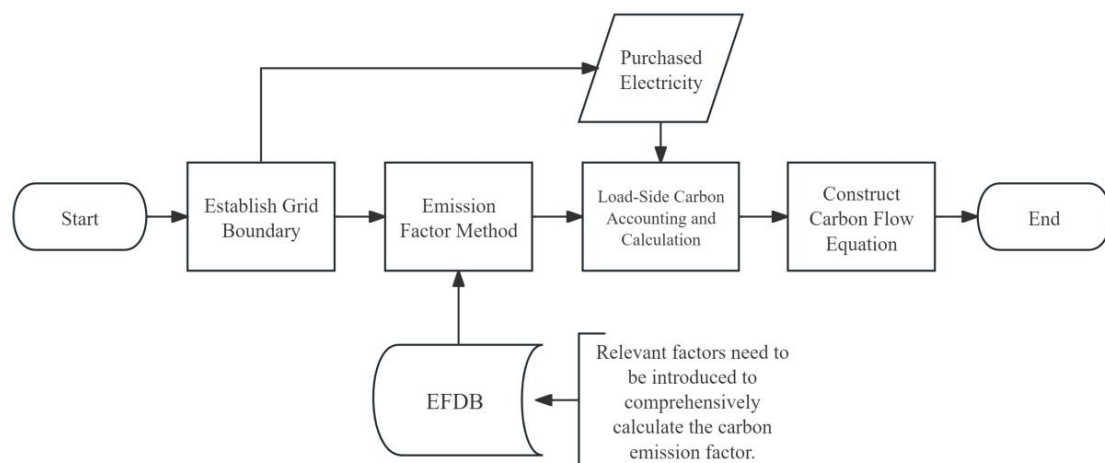


Figure 3. Typical carbon flow calculation process.

The physical information fusion method can effectively improve the accuracy and real-time performance of carbon flow tracking, which fits the power system trend

calculation. By constructing a physical model, based on the tributary carbon flow and node carbon potential, it builds the equilibrium relational equation and node equations, and at the same time collects real-time data such as power generation output, load demand, line loss, etc. by using smart meters, PMUs, SCADA systems, etc., to satisfy the demand for real-time monitoring. Compared with the traditional input-output method, the physical information fusion method is characterized by accuracy, real-time and fine granularity, and can serve smart grid scheduling, user carbon footprint traceability, and carbon market trading.

3.2.2. Blockchain-enabled distributed metering architecture

Blockchain technology is combined with the energy Internet to chronologically connect the data blocks of integrated energy multi-energy systems, grid power trend and carbon flow into a chain to form a chain database, and encrypted with passwords to construct distributed management and complete the shared database in the form of multi-party participation. In blockchain technology, the carbon flow data required for carbon exchange can realize idealized traceability, and other nodes need to be synchronized when a new node joins to realize cross-body data sharing, and the whole process is encrypted to prevent data leakage or tampering.

3.2.3. Key bottlenecks

In the power system, the carbon emission factors of coal power and photovoltaic equipment need to be updated dynamically, especially the frequency of minute-level carbon intensity calibration is extremely high, but the existing system lacks a unified data interface and a real-time calibration mechanism, which leads to a lack of credibility of the calibration results. In addition, carbon flow models based on the fusion of physical information (e.g., grid tidal current equations) are susceptible to parameter mismatches in dynamic scenarios, and problems such as sensor noise or delays are difficult to avoid.

At the level of privacy and trust, the blockchain sharing platform improves data transparency but also brings the risk of privacy leakage. Edge nodes need to handle high-frequency carbon stream data (e.g., 100,000 per second), but limited by device arithmetic (e.g., only supporting AES-128 lightweight encryption), the strength of privacy protection is insufficient. Meanwhile, in the absence of a third-party regulator, the trust mechanism of carbon trading platforms is missing, further exacerbating the conflict between data sharing and privacy protection.

4. Methodology for the Reconfiguration of the Architecture

4.1. Digital Twin-Driven Reconfiguration of Regulatory Architecture

4.1.1. Multi-resolution digital twin construction strategy

The digital twin system of the power system consists of four core parts: equipment physical twin, operation data twin, intelligent control twin and user load twin. Based on the automatic evaluation model of power grid information level proposed by Xu et al, we further propose a “second-minute-hour” three-scale twin architecture for integrated energy systems to realize the whole life cycle management and dynamic synergy of complex systems. The architecture covers diversified needs from real-time control to long-term planning through hierarchical modeling with different time resolutions:

(1). Second-level twin: responsible for real-time control, supporting high-frequency data acquisition and fast response from milliseconds to seconds.

(2). Minute-level twin: combining with Deep Reinforcement Learning (DRL) to optimize resource scheduling and operation strategies within the minute-level time window, solving the problem of multi-energy flow coordination and matching supply and demand. 3. hour-level twin: responsible for real-time control, supporting millisecond-to-second high-frequency data acquisition and fast response.

(3). Hourly twins: Based on big data and machine learning (e.g., LSTM, GNN), predictive models are constructed to analyze the trend of energy demand and the decline of equipment life, and to support long-term planning and macro-strategy formulation, with the time span ranging from several hours to several months.

This multi-resolution architecture effectively improves the flexibility and accuracy of power system regulation, providing a solid technical foundation for the intelligent management of complex systems.

4.1.2. Deep coupling of virtual power plant and carbon flow calculation

Constructing a virtual power plant digital twin system covering equipment, field stations and regions can simulate the carbon footprint through digital twin technology and realize the optimization of virtual power plant scheduling strategy. The system constructs a grid current and carbon flow calculation model in a 3D scenario by endowing the system with physical attributes. For example, Guohua Yue et al. used an electrostatic field equivalence method for model downscaling of a transformer supplied by a 535kV DC circuit breaker, which realized a fast solution with low-latency interaction. In addition, the virtual power plant platform is capable of realizing multi-resolution control of multi-energy systems and supporting carbon flow calculation and traceability functions on the grid side.

4.2. Multi-energy flow coordination mechanism based on quantum game theory

4.2.1. Paradigm leap from non-cooperative games to quantum synergy

Using quantum bit superposition state to simultaneously explore multi-strategy combinations and accelerate equilibrium solving can break through the arithmetic limitation under the resource allocation condition, while quantum entangled state can compress the strategy space, reduce the Nash equilibrium solving complexity from $O(2^n)$ to $O(n^2)$, and the transcendental exponential complexity to the polynomial level, and the relevant research shows that in the micro-network containing 50 producers and consumers, the decision-making efficiency is improved by 76% and carbon emission is reduced by 9.3%, which greatly reduces arithmetic requirements and improves data real-time and accuracy. (Table 1)

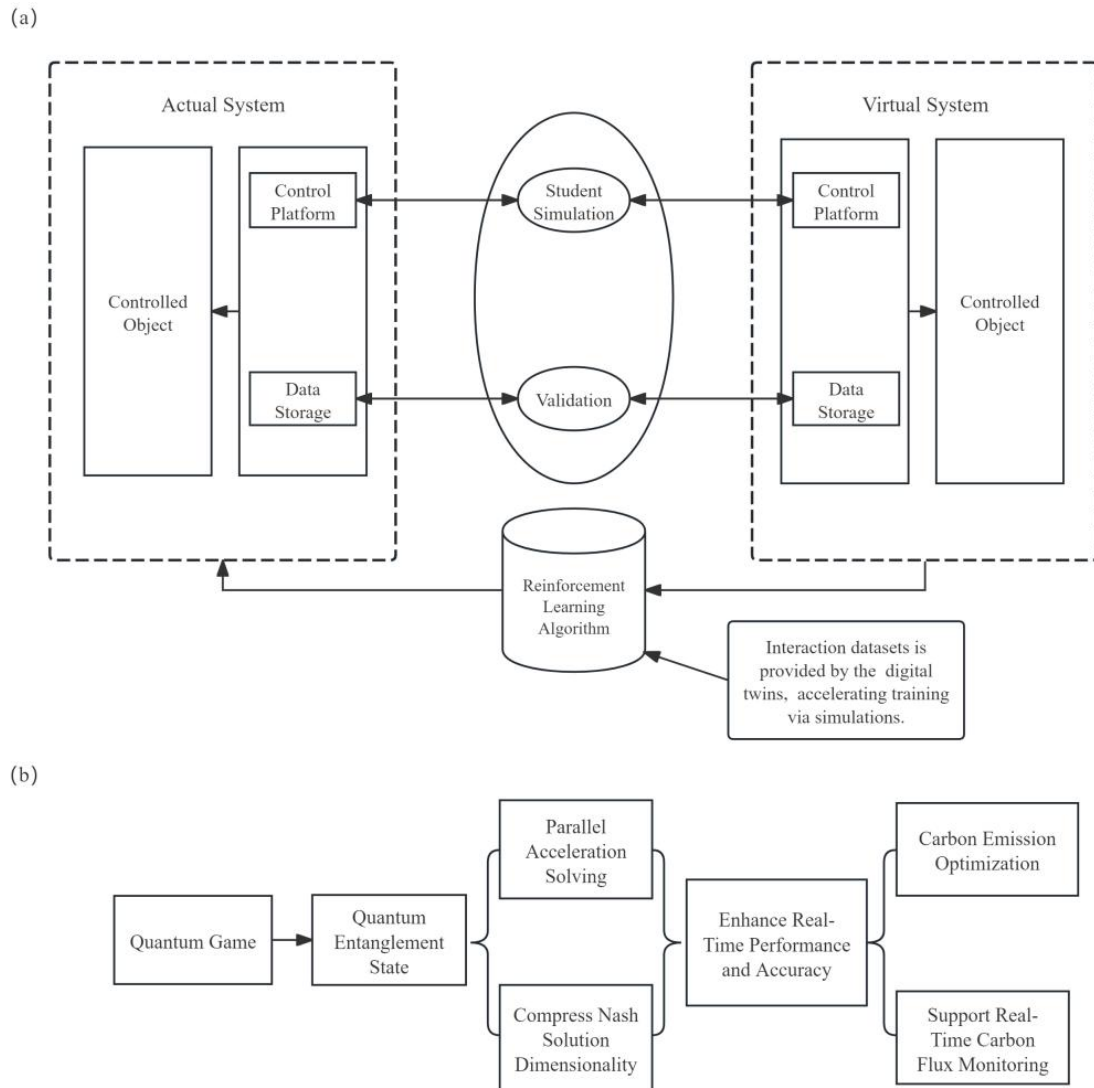


Figure 4. (a) Coupled model of digital twin with its construction of virtual power plant involved in carbon flow calculation. (b) Principle flow of computation and detection of quantum game improvement system.

5. Conclusions

The intelligent regulation system of the energy Internet is the core support for the goal of carbon neutrality, and under the status quo that the core obstacles to the development of the system exist in the synergy of multiple energy systems, grid measurement and regulation, and carbon flow tracking, it is necessary to reconstruct the system by integrating the theories of digital twins, quantum games, and other cutting-edge technologies, and to promote synergistic innovations in policies and market mechanisms. Future research should focus on dynamic carbon measurement standard, edge intelligent equipment R&D and interdisciplinary platform construction, from “technology island” to “system symbiosis”, and ultimately realize the three-dimensional change of energy, information and system.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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