J. Electrical Systems 20-3 (2024): 4936-4946

[1]*Jing Chen

Unified Dynamic Simulation System for Multi-Energy Flows of Electricity, Heat, and Gas in Integrated Energy Systems

Abstract: Integrated energy systems (IES) coordinate heterogeneous energy flows of electricity, heat, and gas to meet diverse load demands and enhance energy efficiency, is a new generation of energy systems that promote sustainable energy development. Simulation systems are essential tools for the analysis, control, and optimization of IES. However, due to the strong coupling of heterogeneous energy flows in IES, existing simulation software often lacks integration, typically focusing on electricity or relying on separate simulations of different energy flows. To address these challenges, this paper proposes a unified simulation technology for electricity, heat, and gas. First, the thermodynamic dynamic simulation capabilities of MATLAB/Simulink are extended using the Thermolib toolbox to create a unified modeling and simulation environment for coupled multi-energy flows. On this foundation, the energy conversion relationships and operating mechanisms of key multi-energy coupling equipment are studied, and dynamic Simulink models of the critical energy devices within the system are developed. Finally, a comprehensive dynamic simulation model for the multi-energy flows of the IES is constructed by connecting energy device models through an energy flow bus. The simulation results demonstrate that this system can effectively simulate the characteristics of electricity, heat, and gas flows across multiple time scales and the complex operating conditions of various energy devices within the MATLAB environment. This approach simplifies the multi-energy flow simulation structure and improves data transmission efficiency for multi-energy flows.

Keywords: Integrated Energy Systems (IES), Heterogeneous Energy Flows (HEF) Dynamic Simulation (DS), Unified Simulation (US).

I. INTRODUCTION

Energy is fundamental to human survival and development. Integrated energy systems (IES) coordinate and complement multiple heterogeneous energy subsystems, including electricity, thermal energy, natural gas, and hydrogen, to meet diverse load demands and improve energy efficiency [1]. As a next-generation energy framework, IES plays a critical role in promoting sustainable energy development. Simulation platforms for IES provide essential tools for testing and theoretical analysis, enabling researchers to explore the complex characteristics of multi-energy flows, evaluate system configurations and operational strategies, and predict system performance. These platforms offer significant research value and practical relevance.

IES simulation platforms can be utilized to assess the impacts of various policies and market mechanisms, such as carbon taxes, renewable energy subsidies, and carbon trading schemes. By simulating different policy scenarios, these platforms assist policymakers in crafting scientifically sound and rational energy policies. For example, some studies have employed simulation platforms to model the effects of carbon trading and green certificate trading on IES, facilitating low-carbon economic dispatch [2][3]. With the advancement of science and technology, cutting-edge tools such as high-performance computing, big data analytics, and artificial intelligence have been integrated into IES simulations. These technologies allow researchers to more accurately model the dynamic behavior of complex energy systems and perform large-scale multi-energy flow data analysis, supporting the development of digital twin-based simulation research. For instance, Stennikov proposed design principles for constructing digital twin systems for IES, encompassing software platform architecture, implementation methodologies, and the computational processes of multi-agent systems [4]. Huang investigated the development and application of digital twin technology within smart city IES, focusing on resolving critical issues in energy internet planning [5]. Further, Li discussed the role of advanced information technologies in driving the digitization of IES, examining the technical value and challenges of applying digital twin technology in market environments[6]. Thus, multi-energy flow simulation technology is essential for advancing IES research and applications.

IES are inherently multi-energy flow systems, integrating electricity, heat, and gas. Current IES simulation systems, however, are predominantly electricity-focused. For instance, the ARIES platform, developed by the U.S. National Renewable Energy Laboratory (NREL), centers on renewable energy integration and grid modernization, aiming to support large-scale energy system research and validation [7]. The PANTHER platform, created by the

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[1] School of Control Science and Engineering, Shandong University, Jingshi Road 17923, Jinan 250061, China
E-mail: jingchen0608@163.com

Pacific Northwest National Laboratory (PNNL), emphasizes optimizing electricity and thermal resources, with a particular focus on enhancing grid reliability and resilience [8].

Power, thermal, and gas systems are heterogeneous energy systems, each with distinct physical properties, transmission dynamics, and mathematical representations. Most existing IES simulation platforms simulate electricity and heat independently, using separate software. Common power simulation tools include the Power System Analysis Software Package and Bonneville Power Administration models, while thermal systems are modeled with software such as ANSYS Fluent and SolidWorks Simulation. Gas systems are typically simulated using tools like FLACS and Fluent. In multi-energy flow simulation, the prevailing approach involves combining mature single-energy flow simulation software. For example, Zhang analyzed the dynamic coupling mechanisms among different energy forms within multi-energy flow systems, constructing a hybrid simulation system that integrates thermoelectric coupling interfaces through data interaction methods and error analysis across different time scales [9]. Sha& KLEIN combined thermodynamic simulation software like TRNSYS with MATLAB/Simulink, a tool commonly used for power simulations, to develop semi-physical real-time simulation test platforms for IES[10] [11]. Additionally, XX developed a functional data interaction interface between TRNSYS and MATLAB, proposing a cross-platform IES simulation framework [12]. The HELICS framework, spearheaded by NREL, links multiple simulation tools to create a unified model suitable for simulating multi-energy systems, including power grids, transportation, and water systems [13].

In summary, while notable progress has been made in IES simulation, both domestically and internationally, the predominant approach remains the integration of multiple single-energy flow simulation tools. This leads to challenges such as data transmission delays and complex system architectures that are difficult to maintain. Therefore, achieving unified simulation of heterogeneous electricity, heat, and gas multi-energy flows within a single software

environment is crucial. To address these challenges, this paper investigates the unified simulation of electricity-heat-gas multi-energy flows and develops an IES multi-energy flow simulation platform within the MATLAB environment.

The remainder of this paper is organized as follows: Chapter 2 provides a brief overview of the structure and operating principles of the integrated energy system. Chapter 3 introduces a unified multi-energy flow simulation framework designed within the MATLAB/Simulink environment, utilizing the Thermolib and Simscope toolboxes. Building on this, Chapter 4 explores the conversion relationships among multiple energy flows and the operational mechanisms of various equipment. It develops dynamic thermodynamic models for equipment based on Thermolib, dynamic electrical models based on Simscope, and interfaces for coupling heterogeneous energy flows. Furthermore, it constructs PID controllers for the equipment to complete the unified dynamic simulation model of multi-energy flows within the integrated energy system. Finally, Chapter 5 presents a case study demonstrating that the simulation system effectively captures the dynamic coupling characteristics of electricity, heat, and gas, as well as the variable operating conditions of energy equipment, all within a unified software environment.

II. OVERVIEW OF INTEGRATED ENERGY SYSTEMS

Fig. 1 illustrates the typical structure of IES, a novel type of energy system that strongly integrates three distinct energy flows: electricity, heat, and natural gas, through multi-energy conversion equipment such as Combined Heat and Power (CHP) units, absorption chillers, and heat pumps. This enables optimization across the entire energy process chain, including production, conversion, storage, transmission, and consumption, with the objectives of enhancing energy efficiency, improving reliability, and minimizing environmental impact. The IES incorporates renewable energy sources like wind and solar power, supplemented by the electrical grid, to meet the system's electricity needs. The CHP unit, serving as the core component of the multi-energy system, converts natural gas into both electrical and thermal energy. The waste heat recovered from the CHP unit is then utilized to drive absorption chillers or directly supply thermal loads to buildings through heat exchangers. Excess thermal energy can be stored in thermal storage tanks and released when needed, thereby increasing the flexibility of thermal energy use. In cases where waste heat is insufficient, gas boilers or heat pumps can be activated to supplement the heat supply.

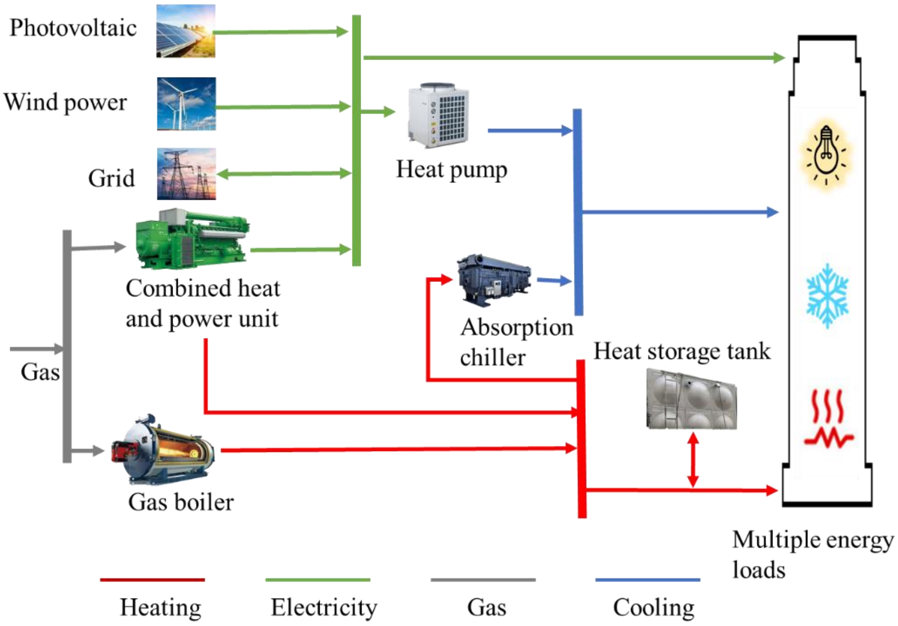


Fig.1 The structure of integrated energy system

III. UNIFIED SIMULATION MODEL STRUCTURE FOR ELECTRICITY, HEAT, AND GAS MULTI-ENERGY FLOWS

The development of simulation systems for integrated energy systems is of paramount importance. Energy facilities are critical infrastructures that directly affect national well-being. Before implementing research findings in practical applications, it is crucial to test and verify their safety and effectiveness. While there are numerous existing projects in integrated energy systems, they often fall short of accurately representing various operational scenarios, particularly under critical and fault conditions. Additionally, given the vast scale of integrated energy systems and the complexity of their components, it is challenging to test and validate existing theoretical research in real-world settings. As a result, simulation remains the primary method for testing and validation.

Due to the coexistence of various heterogeneous energy flows in IES, traditional single-energy flow simulations, which are typically based on different disciplinary backgrounds, face significant challenges. The data interoperability between models for these heterogeneous energy flows is poor, making it difficult to integrate them organically. This lack of cohesion severely hampers collaborative research on multi-energy flows, highlighting the need for a unified simulation environment that can accommodate multiple energy flows seamlessly. Given MATLAB's significant influence in the fields of energy optimization and control, this paper focuses on developing a unified modeling and simulation environment for multi-energy flows using MATLAB/Simulink. Since Simulink does not inherently include a dedicated toolbox for thermodynamic dynamic simulations, it is necessary to extend its capabilities with third-party software to meet the requirements of IES for unified multi-energy flow modeling and simulation.

Thermolib, developed by Eutech Scientific in Germany, is a specialized thermodynamic simulation toolbox for MATLAB/Simulink that is specifically designed for modeling and simulating thermodynamic systems. As shown in Figure 2, Thermolib is primarily based on thermodynamic theory and engineering thermophysics methods to model thermal systems. It offers an extensive library of models and databases, including those for liquid-phase and gaseous thermodynamics, covering a wide range of basic equipment and state-change models commonly used in thermodynamics. These models include pumps, compressors, valves, heat exchangers, storage tanks, chemical reactors, fuel cell stacks, combustors, and more. By utilizing Thermolib, Simulink's capabilities in thermodynamic dynamic simulation can be significantly expanded, enabling more comprehensive and accurate modeling of integrated energy systems.

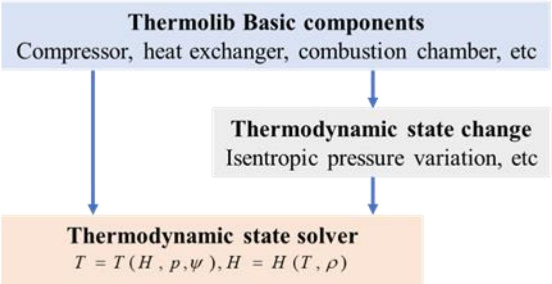


Fig.2 Thermolib model library

Therefore, this paper develops an IES simulation model within the MATLAB/Simulink environment, utilizing the Thermolib thermodynamic simulation toolbox in combination with other model libraries available in Simulink, such as the electrical model library Simscope. The structure of this integrated simulation model is illustrated in Fig.3. Specifically, the model leverages Thermolib to develop comprehensive thermal and gas system models. These include the engine model for CHP units, thermal transmission pipeline models, thermal storage tank models, absorption chiller models, heat pump models, heat exchanger models, building thermal load models, and gas pipeline models. Additionally, the Simscope toolbox is employed to develop detailed electrical system models, which consist of generator models for CHP units, renewable energy models, building electrical load models, and grid models.

By integrating these models, the simulation platform provides a robust and cohesive environment for simulating the dynamic interactions between electricity, heat, and gas within an integrated energy system. This setup allows for a detailed analysis of the performance and behavior of various energy components under different operational scenarios, contributing to the optimization of energy systems for improved efficiency and sustainability.

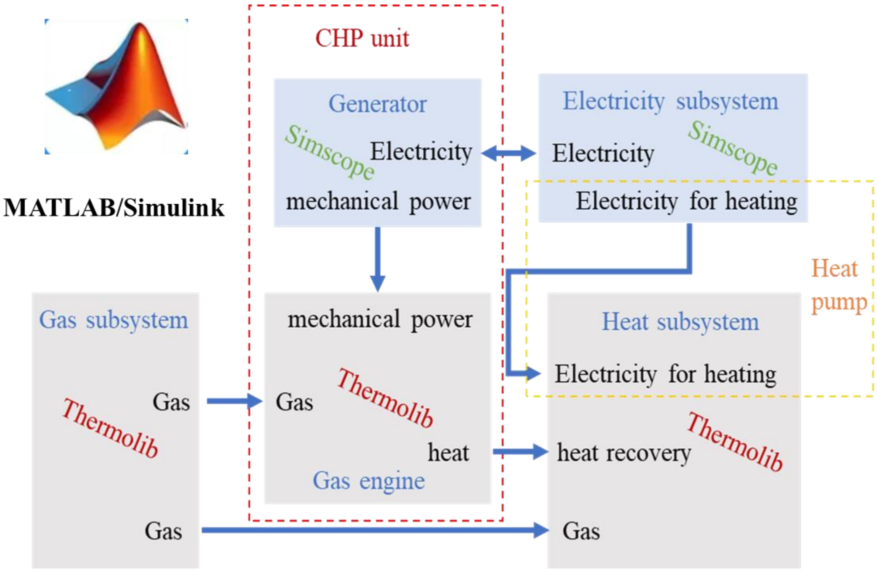


Fig.3 Unified Simulation Model Structure Diagram for Electricity, Heat, and Gas Multi-Energy Flows

For the coupling between multi-energy flows, coupling power data is used as the interface between different energy flow models. Based on the principle of energy conservation, the coupling power remains consistent across different energy flows. Using this coupling power as an interface for the integration of multi-energy flows facilitates unified modeling and is highly advantageous for subsequent research, particularly in decoupled parallel real-time simulations.

By utilizing various sub-software tools within a unified environment, this approach accommodates the modeling differences and simulation requirements of different energy flows. Since all sub-software runs on a common underlying platform, there are no data exchange issues between them, ensuring seamless data integration. This method simplifies the process of modeling multi-energy flows, providing a cohesive framework that enhances both the accuracy and efficiency of the simulation process.

Moreover, the ability to model multi-energy systems in a unified environment allows for more comprehensive analysis and optimization of energy systems, promoting better coordination and interaction between electricity, heat, and gas flows. This integrated approach not only supports the accurate simulation of energy dynamics but also contributes to the development of more efficient and sustainable energy management strategies.

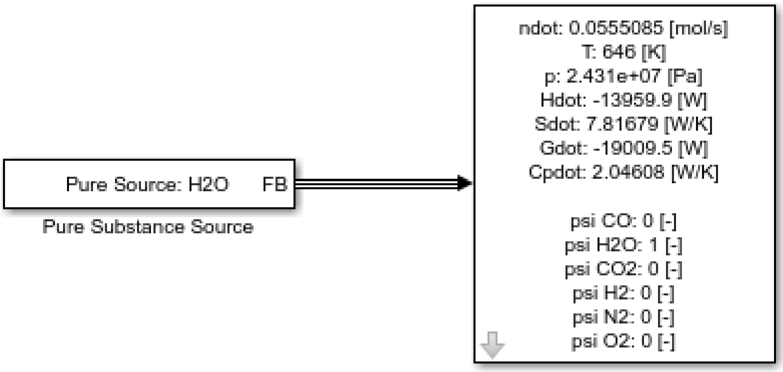
IV. DYNAMIC SIMULATION MODEL OF MULTI-ENERGY FLOW EQUIPMENT

Moreover, in IES, there are alternating effects between various heterogeneous energy flows, some of which operate at different speeds and timescales. Relying solely on energy conversion relationships to establish steady-state power conservation models fails to capture the dynamic interactions and transient processes between different energy flows. This limitation prevents a comprehensive understanding of how these flows interact under varying conditions and timeframes. To more accurately represent the complex dynamic characteristics of IES, it is essential to develop systematic dynamic mechanism models. These models should not only account for the energy conversions and interactions in a steady state but also simulate the transient behaviors and dynamic responses of the energy flows. By incorporating the temporal variations and the interplay between fast and slow energy streams, these dynamic models provide a more realistic and detailed depiction of how integrated energy systems operate in real-world scenarios.

A. Thermodynamic signal bus

The energy signal bus structure of the equipment model based on Thermolib is shown in Fig.4. Based on this signal bus, the thermodynamic calculation processes of all Thermolib simulation models include a comprehensive range of signals, such as mass flow rate, molar flow rate, pressure, temperature, entropy flow, enthalpy flow, Gibbs free energy flow, molar composition, and gas ratio. These parameters are crucial for accurately modeling the behavior of various thermodynamic systems, allowing for detailed analysis of energy conversion processes.

By capturing such a wide array of thermodynamic properties, the Thermolib simulation models provide a robust framework for simulating complex interactions within IES. This level of detail enables researchers to assess how changes in one parameter might impact the overall system, supporting the development of more efficient and reliable energy management strategies. Furthermore, the inclusion of both macroscopic and microscopic properties, like molar composition and gas ratio, ensures that the simulations can account for chemical reactions and phase changes, which are essential for accurate modeling of real-world energy systems.



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ndot: 0.0555085 [mol/s]
T: 646 [K]
p: 2.431e+07 [Pa]
Hdot: -13959.9 [W]
Sdot: 7.81679 [W/K]
Gdot: -19009.5 [W]
Cpdot: 2.04608 [W/K]

psi CO: 0 [-]
psi H2O: 1 [-]
psi CO2: 0 [-]
psi H2: 0 [-]
psi N2: 0 [-]
psi O2: 0 [-]
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Fig. 4 Signal buses of Thermolib simulation model

B. Dynamic model of energy devices

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The thermodynamic model of the gas turbine engine is illustrated in Fig.5. As shown in the figure, the engine operation involves four main thermodynamic processes.

Firstly, air enters the compressor of the gas turbine, where it is compressed, resulting in increased pressure and temperature. This compression process is ideally isentropic, meaning that the entropy remains constant. Next, the compressed high-temperature, high-pressure air flows into the combustion chamber. In the combustion chamber, fuel is injected and combusted, releasing a significant amount of thermal energy, which further raises the temperature of the gases, while the pressure remains relatively constant. This process occurs under approximately constant pressure conditions.

Subsequently, the high-temperature gases exit the combustion chamber and enter the turbine, where the gases expand, performing work that drives the turbine, the attached compressor, and other mechanical devices. The expansion process is also typically considered isentropic, where the gas performs work while both its temperature and pressure decrease. Finally, the gases, having done their work, are expelled into the atmosphere with a lower temperature and pressure than they had before entering the combustion chamber, completing a Brayton cycle. The model depicted in Fig.5 comprehensively describes these four thermodynamic processes.

The generator component of the gas turbine model is constructed using the synchronous machine from the power system simulation toolbox, as shown in Fig. 6. To integrate the engine and generator models, the mechanical energy output from the engine, represented by Signal Output Port 1 in Fig. 5, is connected to Signal Input Port 1 of the generator model depicted in Fig. 6. This connection creates a complete gas turbine simulation model, accurately representing the coupling between the engine and the generator.

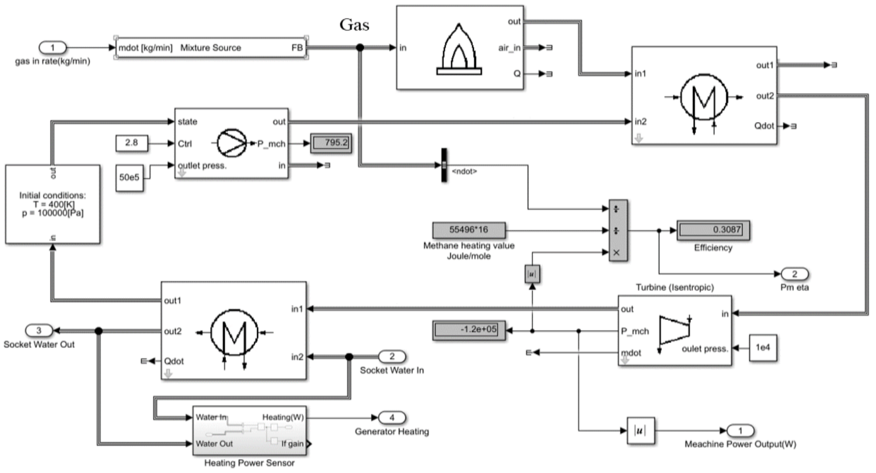

Fig.5 Simulink simulation model of an engine based on Thermolib toolbox

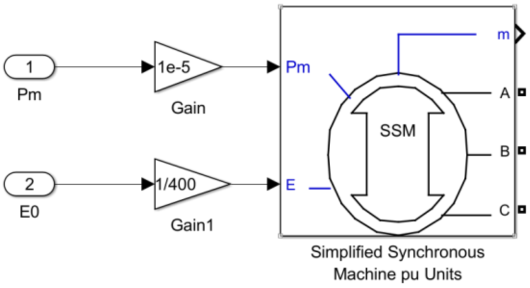

Fig. 6 Simulink simulation model of. a generator based on Simscope toolbox

The operational controller of equipment is essential for ensuring that energy devices operate according to their output plans. For a gas turbine, the electrical power output of the generator is typically controlled by adjusting the intake rate of natural gas. Thus, the intake rate of natural gas is chosen as the output signal of the controller, while the actual electrical power output of the generator serves as the feedback signal. The desired electrical power output of the generator is set as the reference value.

Using these parameters, a Proportional-Integral (PI) control algorithm, as described in Equation 1, is implemented to build the gas turbine operational PI controller, as shown in Fig. 7. This PI controller is designed to regulate the intake rate of natural gas to ensure that the generator's output matches the setpoint, thereby maintaining stable and efficient operation of the gas turbine under varying load conditions.

$$u(t) = K_p e(t) + K_i \sum_0^t e(t)dt$$

where u(t) represents the control variable output by the controller at time t， Kp and Ki are the proportional gain and integral gain of the controller, respectively， e(t) denotes the error at time t, which is the difference between the setpoint (desired output) and the actual output of the controlled object.

The PI control mechanism continuously adjusts the natural gas flow based on the difference between the actual output and the desired setpoint, minimizing error and optimizing performance. This approach is crucial for dynamic control and efficient energy management in IESs, providing a reliable method for maintaining consistent power output in response to fluctuating energy demands.

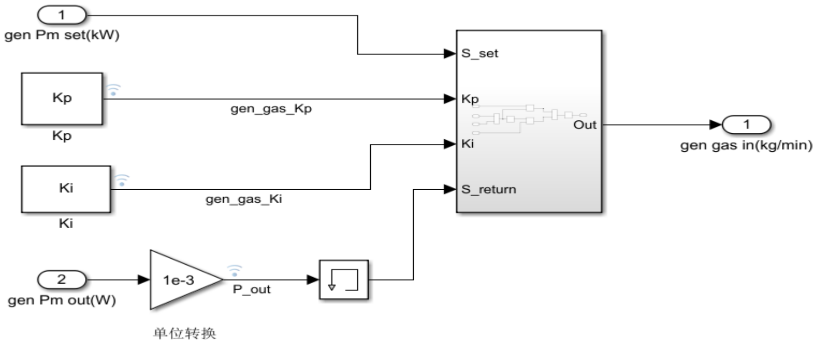

Fig. 7 PI Controller for equipment operation

The dynamic simulation models for the heat pump, boiler, and absorption chiller can be constructed using a similar approach to that of the gas turbine model described above. In addition, components such as thermal storage tanks, building thermal loads, gas pipelines, and heat transmission pipelines are modeled using the Thermolib toolbox, without the need for separate operational controllers. For purely electrical equipment, such as wind turbine models, photovoltaic (PV) generation models, and battery storage systems, more established power system simulation toolkits Simscope are utilized. Simscope toolbox provides well-developed models and functions that do not require further elaboration in this context. By leveraging these specialized toolkits and modeling strategies, the simulation environment can accurately represent the dynamic interactions and performance characteristics of various energy systems. This comprehensive approach ensures that all components, whether thermal, electrical, or gas-based, are effectively integrated into the MATLAB, allowing for a holistic analysis of the integrated energy system's behavior under different operational scenarios.

C. IES simulation model

The electrical components of the CHP unit, photovoltaic (PV) generation systems, and building electrical loads, which are modeled using Simscope, are connected to create the electrical subsystem simulation model, as shown in Fig.8. Based on the energy bus shown in Fig. 4, the thermodynamic equipment models developed using Thermolib—including the engine component of the CHP unit, heat exchangers, absorption chillers, gas boilers, natural gas sources, valves, and building thermal loads—are interconnected to form the thermal and gas subsystems simulation model. Based on the coupling relationships of the equipment, the simulation models of the thermal, gas, and electrical subsystems are interconnected to form a complete integrated energy system simulation model, which is shown in Fig.9.

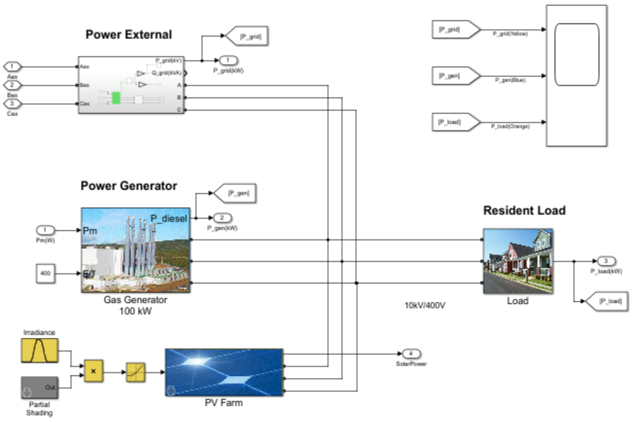

Fig.8 Simulation model of electricity subsystem

To complete the IES simulation model, the mechanical energy output from the engine is linked to the mechanical energy input of the generator. This connection effectively combines the thermal, gas, and electrical subsystems into a unified simulation framework, allowing for comprehensive analysis of the integrated energy system's performance across different energy domains.

This integrated simulation model facilitates the examination of dynamic interactions between the thermal, electrical, and gas subsystems, providing valuable insights into the overall efficiency and responsiveness of the energy system under varying operational conditions. By accurately modeling the interdependencies among these subsystems, the simulation helps in optimizing the energy system's design and operational strategies, ultimately contributing to improved sustainability and reliability.

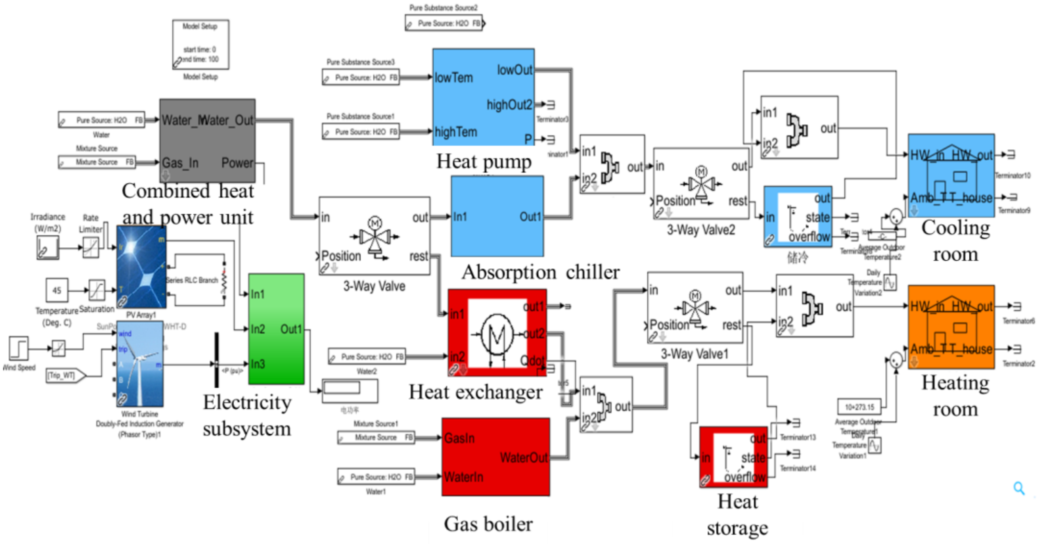

Fig.9 The simulation model of the integrated energy system

D. *Case study*

To validate the effectiveness of the simulation system, the typical integrated energy system simulation model was put through a series of simulation runs. The main parameters for the energy equipment within this integrated energy system are listed in Tab.1. A day-ahead optimal scheduling solution for the integrated energy system was determined using a genetic algorithm, and the optimized output data for each energy device were fed into the corresponding interfaces of the simulation model.

Tab. 1 Parameters of major energy equipment

Devices	Capacity
Combined heat and power unit	280kW
Absorption chiller	280 kW
Heat pump	210 kW
Gas Boiler	750 kW
Photovoltaic	100 kW
Wind power	100 kW

Supported by the proposed unified simulation technology for multi-energy flows of electricity, heat, and gas, the simulation system operated smoothly. The results of the simulation are as follows.

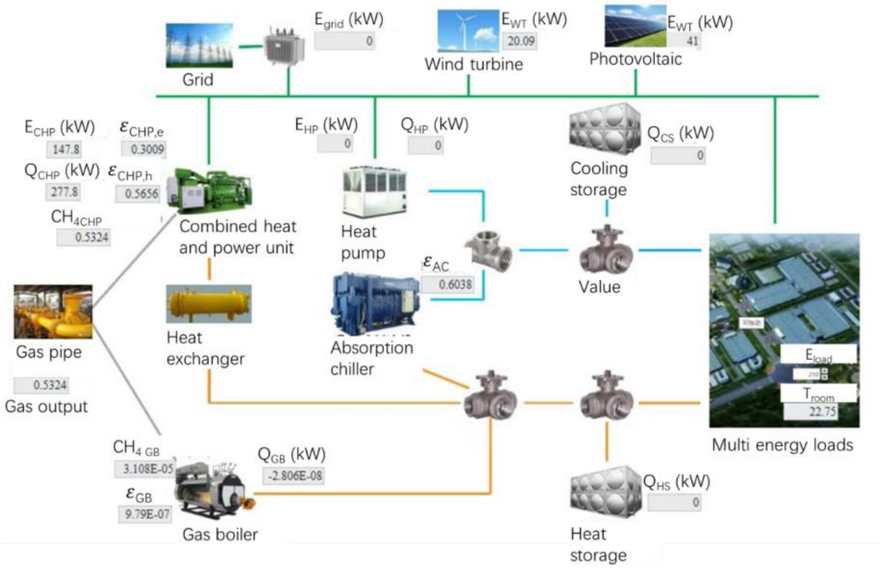

Fig. 10 Integrated energy system multi-energy flow overall monitoring diagram

The overall multi-energy flow monitoring interface of the simulation system is shown in Fig.10. This monitoring interface provides a clear visual representation of the multi-energy flow structure and can also display real-time data on the output values of energy devices, operating efficiency, and energy supply quality. As depicted in the figure, at the specific moment shown, the photovoltaic and wind power outputs are 20.09 kW and 41 kW, respectively. CHP unit generates 147.9 kW of electricity. Together, these sources meet the electrical load demand, thereby eliminating the need for grid electricity purchases and achieving regional power balance. Additionally, all 277.9 kW of thermal energy produced by the CHP unit is utilized to meet the building's thermal load requirements. This ensures that the indoor temperature reaches an ideal level of 22.75 degrees Celsius without the need for additional heating from gas boilers or heat pumps, thereby achieving thermal energy balance. Furthermore, due to the absence of real-world negative factors such as aging or dust accumulation, the simulated electrical efficiency of the CHP unit is approximately 0.3, while the thermal efficiency is around 0.53, indicating an ideal operational state.

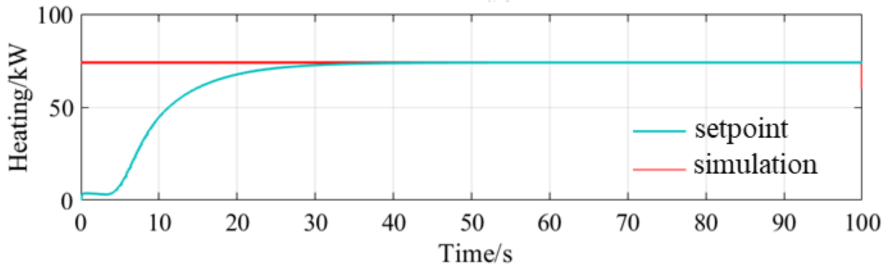

Fig.11 Dynamic output curve of heating from the gas boiler

Moreover, due to the Thermolib toolbox's detailed characterization of thermal dynamics and the presence of device-level controllers, the simulation system effectively captures the dynamic characteristics of energy equipment. This makes it well-suited for studying the impact of load uncertainty and the variability of renewable energy sources, such as wind and solar power, on the operation of integrated energy systems. As shown in Fig.10, the dynamic output curve of thermal energy from the gas boiler under varying operating conditions is depicted. The figure illustrates that, due to the dynamic delays in heat transmission and heat exchange and the devices controller, the thermal output of the gas boiler stabilizes at the set value of 75 kW approximately 30 seconds after the change in conditions.

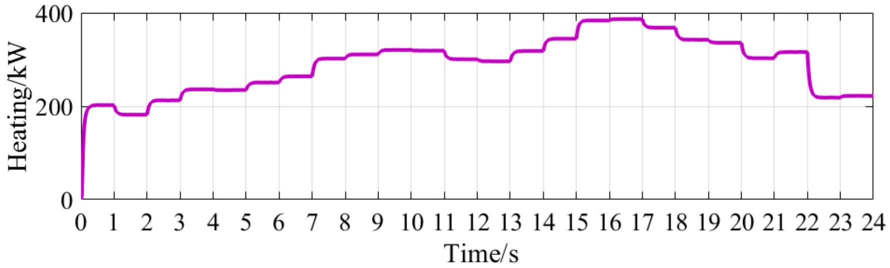

Fig.12 Thermal energy output curve of the combined heat and power unit

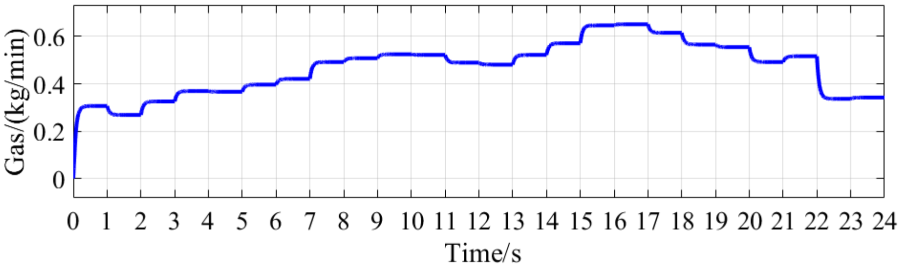

Fig.13 Natural gas consumption rate curve of the integrated energy system

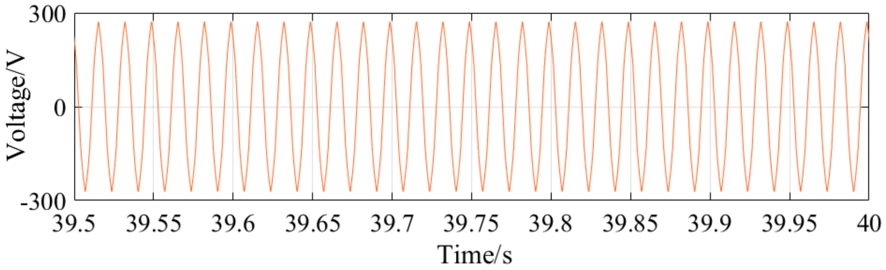

Fig.14 Output single-phase voltage curve of the combined heat and power unit

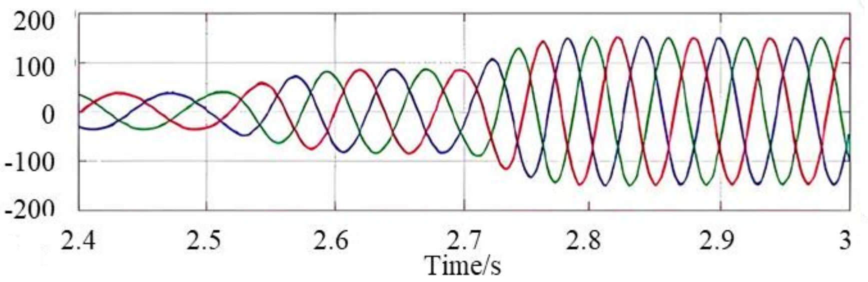

Fig.15 Output three-phase current curves of the wind turbine

Fig.12 shows the 24-hour thermal energy output curve of the CHP unit. From the graph, it is evident that the CHP unit's load rate peaks at 16:00 and is relatively low during the night from 23:00 to 6:00, reflecting the influence of human activity patterns and ambient temperature variations.

Correspondingly, the 24-hour natural gas consumption of the integrated energy system is illustrated in Fig.13. Since the gas boiler does not contribute to the output, the total natural gas consumption of the system equals the gas consumption of the CHP unit. Although the operational efficiency of the CHP unit varies under different conditions, the rate of natural gas consumption generally follows a trend similar to that of its thermal energy output.

Fig.14 and Fig. 15 display the output voltage curve of the CHP unit and the output current and voltage curves of the wind turbine, respectively.

In summary, the simulation system effectively achieves a unified simulation of electricity, heat, and gas within the MATLAB environment, accurately reflecting the dynamic interactions among these energy flows.

V. CONCLUSION

IES offer significant advantages, including being green, low-carbon, safe, and efficient. Developing IES is a key strategy for achieving sustainable development. Simulation systems are fundamental tools for the analysis, control, and optimization of integrated energy systems. In response to the current challenges posed by the strong coupling of heterogeneous energy sources—electricity, heat, and gas—and the lack of unified multi-energy flow simulation software, this paper proposes the establishment of a unified simulation system for electricity, heat, and gas flows. By integrating Thermolib and Simscope, a unified MATLAB simulation environment for multi-energy flows was developed. This simulation environment includes multi-modal, full-condition dynamic simulation models for key coupling equipment within IES, enabling unified simulation of the dynamic characteristics of electricity, heat, and gas flows, as well as the variable operating characteristics of energy devices within the MATLAB environment. This approach avoids the data exchange delays and complex simulation architectures associated with traditional multi-energy flow simulations using different software, providing a convenient and highly accurate simulation platform for the development of integrated energy systems.

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