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Optimization of Energy Flow in Urban Micro-grids: A Thermodynamic Analysis-Based Approach

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ABSTRACT

As the issues of global energy crisis and climate change are becoming increasingly prominent in the world, urban microgrids have received widespread attention as an effective way to improve energy utilization efficiency and reduce environmental pollution. Among them, the cogeneration of heat and power (CHP) system is considered as one of the key technologies to improve the energy efficiency of urban microgrids because it can provide both electricity and heat. However, how to optimize the energy flow scheduling for CHP systems, especially in the context of increasing renewable energy sources, has become a hot topic of current research. Existing studies usually rely on the traditional dual-time-scale scheduling strategies, namely day-ahead scheduling and real-time scheduling, but both have obvious limitations in dealing with the uncertainty and volatility of new energy sources. To address the above problems, this paper proposes a thermodynamic analysis-based scheduling method for optimizing the energy flow in the CHP system of urban microgrids. First, this paper introduces the concepts of rolling schedule and real-time schedule to improve the traditional time-scale scheduling method, so as to enhance the system's adaptability to new energy power fluctuations. Second, for the absorption CHP system, this paper proposes a thermal cycle performance optimization strategy, which significantly improves the utilization efficiency of thermal energy through the cascaded recycling of system waste heat. Through these two innovations, this study not only realizes a more accurate and efficient energy management, but also provides a new strategy for the sustainable development of urban microgrids.

1. INTRODUCTION

With the continuous growth of global energy demand and the increasingly-sever problems of environmental pollution and climate change, traditional centralized energy systems are facing major challenges [1, 2]. As a flexible and efficient distributed energy system, urban microgrids not only help to improve the efficiency of energy use, but also are expected to significantly reduce greenhouse gas emissions by integrating renewable energy sources, energy storage devices, and CHP facilities on a local scale [3-5]. However, how to optimize the energy flow, especially in the context of CHP, has become a key issue to improve the operational efficiency of urban microgrids [6, 7].

In such case, we can see that researching the energy flow optimization of urban microgrids is very important and has high theoretical value and practical significance [8]. With the help of thermodynamic analysis, we can have a deeper understanding of the basic laws of energy conversion and flow in CHP system, then more efficient and stable energy management strategies can be developed [9-11], which will be an important contribution to realizing energy conservation and environmental protection goals, as well as to improving economy and reliability of urban energy systems [12-14].

Existing studies on the optimization of energy flow in urban microgrids mostly rely on the traditional dual-time scale scheduling approach, i.e., day-ahead planning and real-time scheduling [15, 16]. Although this approach can deal with the energy allocation problem to some extent, it often lacks flexibility and accuracy when facing the volatility and uncertainty of new energy access [17, 18]. In addition, the existing methods are also deficient in the optimization of thermal cycle performance, failing to give full play to the potential of the CHP system, resulting in low energy recovery efficiency and the overall energy efficiency of the system to be improved [19-21].

The main content of this paper revolves around the optimization of energy flow based on thermodynamic analysis in urban microgrids, focusing on two aspects: firstly, an optimal scheduling strategy for energy flow in CHP system is proposed to refine the time scale by introducing rolling and real-time schedules in order to improve the system's ability to accommodate new energy power. Second, the thermal cycle performance of the absorption CHP system in an urban microgrids is optimized to achieve the cascaded recycling of the system's waste heat, which improves the system's energy utilization and ensures the reasonable distribution of power and heat. The innovation of this study is the combination of thermodynamic principles and energy flow management, which provides a new solution for the sustainable development of urban microgrids and has important theoretical and applied research value.

2. ENERGY FLOW OPTIMIZATION SCHEDULING IN URBAN MICROGRID CHP SYSTEM

Urban microgrid CHP systems face significant challenges under traditional scheduling methods, primarily due to inadequate adaptability to the characteristics of new energy generation, especially in handling the randomness and volatility of new energy generation. This volatility can lead to deviations between traditional day-ahead scheduling plans and actual load demands, making it difficult to precisely predict real-time load requirements. When systems rely on automatic generation control units for real-time adjustments to accommodate load variations, they may still fail to meet load demands once these units reach their adjustment capacity. In such scenarios, manual intervention by schedulers becomes necessary to adjust unit outputs to meet demands, often at the expense of economic principles, namely achieving energy supply at the lowest cost.

This study proposes an optimized scheduling method for energy flow in urban microgrid CHP systems, as illustrated in Figure 1. By introducing rolling planning and real-time planning between day-ahead scheduling plans and automatic generation control, the method presented in this research adapts more flexibly to the immediate changes in energy demand, particularly in the face of uncertainty and fluctuations in new energy generation. Moreover, this approach allows for the adjustment of prediction models and scheduling strategies considering prediction errors and new energy generation fluctuations. Thus, as much new energy power as possible is accommodated, increasing the renewable energy utilization of the system. Refined time scales allow the system to respond faster to load changes, reducing the risk of system instability due to response lags. Rolling schedule and real-time schedule provide a continuous adjustment mechanism which enables the system to maintain stable operation even in case of large fluctuations in new energy output.

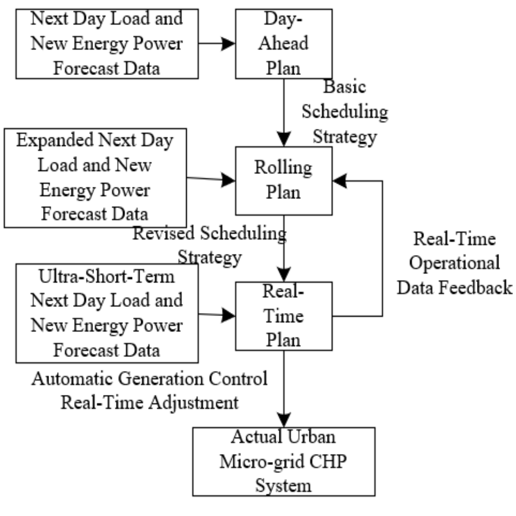


Figure 1. Overall flowchart of the energy flow optimization scheduling scheme in urban micro-grid CHP system

2.1 Day-ahead plan

Day-ahead plan is a scheduling method based on forecast data of load and new energy power of the next day before the actual operation. This kind of plan is the core in traditional power system scheduling, which involves determining generating unit combinations, start/stop status, and power exchange of inter-regional contact lines, so as to optimize the generation output of each unit. However, when large-scale wind power and other new energy sources are connected to the system, the day-ahead plan will be limited by prediction accuracy, which makes it difficult to ensure the safe and stable operation of the system. The reason is that the high volatility and uncertainty of new energy sources such as wind power can cause a large deviation between the actual power generation and the predicted value, which makes it difficult for the day-ahead prediction-based scheduling plan to accurately meet the actual load demand. This paper aims to solve this problem by establishing a day-ahead optimization scheduling model for the energy flow of CHP system in urban microgrids, so as to improve the accuracy and economy of scheduling. The model is established based on more accurate prediction data and scheduling model, it can reduce the prediction error caused by volatility of new energy generation, thereby meeting the actual load demand more accurately. The optimal start/stop status and output plans are designed in advance to adapt to the new energy grid connection and ensure the safe and stable operation of the system when connecting to large-scale wind power. With the goal of minimizing the overall cost of system operation, it can maximize cost-effectiveness by optimizing unit output and start/stop strategies.

The optimization targets of the constructed day-ahead optimization scheduling model for the energy flow in urban microgrid CHP system include the output of generation units, the start-stop status of units, power exchanges across interconnections, scheduling of energy storage devices, and load response. The model assumes the existence of certain load forecasting and new energy power forecasting methods, with errors within an acceptable range. It is also assumed that the intra-day scheduling plan will follow the optimized day-ahead plan, with only necessary corrections made to the unit outputs. The capacity and safety constraints of the transmission network, as well as the capacity and charging/discharging efficiency of energy storage devices, are all known factors.

2.2 Rolling scheduling and real-time scheduling

Due to the high uncertainty associated with new energy generation, the accuracy of predictions is crucial for effective scheduling. Traditional automatic generation control systems may face regulatory pressures with the large-scale integration of new energy sources. Rolling scheduling, by continually integrating the latest generation and load information on the day of operation, can reduce plan deviations caused by prediction errors. The essence of rolling scheduling is dynamic adjustment; it updates and corrects the output plan of units for the remaining period based on real-time data feedback during operation, building upon the day-ahead plan. This approach better adapts to the actual system state and market conditions. Rolling scheduling ensures safe and stable system operation amidst new energy output fluctuations and load changes by introducing safety checks following the day-ahead plan. These checks, as an ongoing process, help prevent potential operational risks. Figure 2 presents an illustrative diagram of the duration of day-ahead and intra-day scheduling plans.

The rolling scheduling-based urban microgrid CHP energy flow optimization scheduling model aims to reflect the total operating cost of the entire system in its objective function. This includes costs associated with power generation, start-up and shut-down of units, maintenance, environmental impact, and others. This may involve a multi-objective optimization problem, necessitating a balance among various cost factors. Assuming the starting moment of the rolling scheduling is denoted by *ts*, and the total cost for the remaining time of the system is represented by *D*', the objective function for the rolling scheduling is given as follows:

$$MIN\ D' = \sum_{s=ts}^{S}\sum_{u=1}^{v}\left(Z_{DI} + Z_{PL} + Z_{RS} + Z_{ZIES}\right)\Delta s \tag{1}$$

At the start of each rolling period, actual operational data from the previous period, including electricity generation, load, and new energy output, along with the latest forecast information, are collected. The current state of the system is analyzed, which encompasses the start-stop status of units, energy storage status, and load demand. Further, based on actual conditions and new forecast data, it is determined when to initiate the rolling scheduling and when the next update should occur. Assuming the sequence number of the rolling scheduling for the day is represented by *RANK*, the following formula calculates the starting moment of the rolling plan scheduling:

$$ts = 4\times\left(RANK - 1\right) \tag{2}$$

Accurately defining constraints is crucial to ensuring that the constructed model operates within technical and safety requirements. Regarding energy balance constraints, at any given moment, the total electricity generation of the system must equal the total system load plus transmission losses. The thermal output of CHP units, along with the heat supply from electric boilers and heat storage tanks, must meet the thermal load demand, considering thermal losses. In terms of unit output constraints, the actual output of all generator units must stay within their minimum and maximum technical output ranges. The rate of output change for each unit must be within its technically specified range. Concerning unit ramping constraints, the rate of output adjustment of a unit cannot exceed its maximum permissible value, and the minimum reduction rate must be considered when decreasing output. For energy storage constraints, the charging and discharging power of energy storage devices must not exceed their maximum charging/discharging power. The state of the energy storage devices must always remain within the minimum and maximum capacity limits. During charging and discharging, the charging/discharging efficiency of the storage devices must be considered.

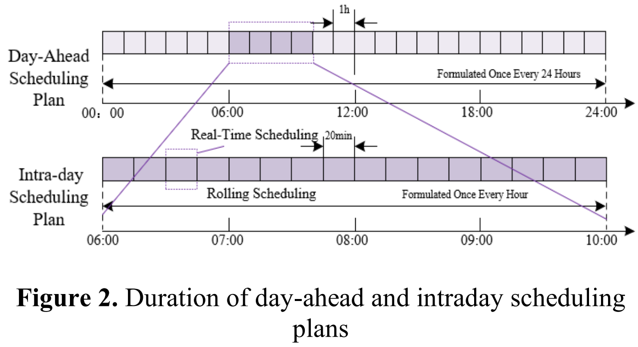


Figure 2. Duration of day-ahead and intraday scheduling plans

The day-ahead plan gives the optimal generation plan based on forecast data, while the plan may need to be adjusted in actual operation due to fluctuations in new energy generation and load. At the same time, large changes in unit output may lead to increased costs, such as frequent startups and shutdowns that increase maintenance costs and fuel consumption. Based on above reasons, this study adds unit output deviation constraints to the scheduling model of the rolling plan to ensure that the rolling plan can be smoothly connected with the previous day's plan during the dynamic adjustment process, and to maintain the stability and reliability of system operation. Specifically, an allowable range of output deviation is set for each unit, which should be based on the technical characteristics of the unit and the operational safety requirements of the system. Based on real-time data and forecast information, dynamically adjust the output of the units to stay within the allowable range of deviation while meeting the load demand. Ensure that the sum of all unit output deviations does not lead to system imbalances, taking into account the uncertainty and volatility of renewable energy sources. Mechanisms are set to manage the risk of contract violation due to excessive output deviations, including reserve services and emergency response measures. Assuming the rolling plan generation power of thermal power unit *u* at moment *s* is represented by $O^{RO}{}_{H,u,s}$, the day-ahead plan generation power of thermal power unit *u* at moment *s* is represented by $O^{DAY}{}_{H,u,s}$, the upper limit of thermal power unit *u*'s generation power is represented by $O^{MAX}{}_{H,u}$, and the constraint multiplier is represented by β, the following expression provides the unit output deviation constraint condition:

$$\left|O_{H,u,s}^{RO} - O_{H,u,s}^{DAY}\right| \le \beta O_{H,u}^{MAX} \tag{3}$$

Assuming that for a CHP unit *u* at moment *s*, the rolling plan generation power is denoted by $O^{RO}{}_{ZGO,u,s}$, the day-ahead plan generation power is denoted by $O^{DAY}{}_{ZGO,u,s}$, the upper limit of generation power is denoted by $O^{MAX}{}_{ZGO,u,s}$, and the constraint multiplier is represented by α, the following relationship can be established:

$$\left|O_{ZGO,u,s}^{RO} - O_{ZGO,u,s}^{DAY}\right| \le \alpha O_{ZGO,u}^{MAX} \tag{4}$$

Furthermore, this paper proposes an optimized scheduling model based on real-time planning for the energy flow in urban microgrid CHP system. Real-time planning, relying on ultra-short-term forecast data, allows for detailed correction of deviations in the rolling plan. Given that ultra-short-term forecasts cover a shorter time frame (usually the next 15 minutes to an hour), their accuracy is higher, aiding in more precise alignment between the generation plan and actual load. Through precise power control, the real-time plan ensures that automatic generation control units have sufficient regulatory capacity to deal with sudden power changes, thereby ensuring system stability. This method also adjusts the basic operating point of each unit based on the latest system information and forecast data. Such adjustments ensure that units operate at output levels closer to actual demand, thus improving system operational efficiency.

The objective function is the core of the urban microgrid CHP energy flow optimization scheduling model based on real-time planning. It defines the goal of optimization, i.e., the state that the optimization process aims to achieve. For real-time planning, the objective function seeks to find the least costly adjustment path, ensuring that actual demands are met while avoiding unnecessary economic expenses, and ensuring that all adjustments do not impact system stability and the continuity of power supply. Assuming the adjustment cost for the u-th thermal power unit is represented by $Z''_{H,u}$, and the adjustment cost for the u-th CHP unit is represented by $Z''_{ZGO,u}$, the total adjustment cost for the system in the next scheduling period is represented by D''. The following expression provides the objective function:

$$MIN\ D'' = \sum_{u=1}^{v} Z''_{H,u} + Z''_{ZGO,u} + Z_{ZIES,u} \tag{5}$$

The real-time scheduling model must consider the adjustment costs of different types of units. For thermal power units, adjustment costs are typically associated with fuel consumption and unit efficiency. Both the adjustment path and rate of a unit affect the amount of fuel consumed. The adjustment costs for CHP units include not only the costs of electrical adjustment but also the stability of heat supply and changes in efficiency. This paper comprehensively considers the adjustment costs of all units. Assuming the adjustment cost for thermal power units is represented by Z''_H, the real-time plan generation cost for thermal power units by $Z_{H,RE}$, and the rolling plan generation cost for thermal power units by $Z_{H,RO}$. The following expression provides the formula for the adjustment cost of thermal power units:

$$Z''_H = \left| Z_{H,RE} - Z_{H,RO} \right| \tag{6}$$

Assuming the adjustment cost for CHPunits is represented by Z''_{ZGO}, the real-time plan generation cost for CHPunits by $Z_{ZGO,RE}$, and the rolling plan generation cost for CHPunits by $Z_{ZGO,RO}$, the adjustment cost for CHPunits can be calculated using the following formula:

$$Z''_{ZGO} = \left| Z_{ZGO,RE} - Z_{ZGO,RO} \right| \tag{7}$$

The constraints of the urban microgrid CHP energy flow optimization scheduling model based on real-time planning are consistent with those based on the rolling plan. Given that real-time planning needs to ensure system stability in the short term, and that power system supply and demand must be balanced at all times, even minor deviations could cause fluctuations in frequency and voltage. Introducing output deviation constraints ensures that unit outputs remain within a safe operating range, preventing system instability. It also maintains power quality, preventing power quality issues caused by real-time load changes. Assuming the real-time plan generation power for thermal power unit u at moment s is represented by $O^{RE}_{H,u,s}$, the constraint for increased unit output deviation is given by the following formula:

$$\left| O^{RE}_{H,u,s} - O^{RO}_{H,u,s} \right| \le \beta O^{MAX}_{H,u} \tag{8}$$

Assuming the real-time plan heating power for CHPunit u at moment s is represented by $O^{RE}_{HGO,u,s}$, then the following relationship can be established:

$$\left| O^{RE}_{ZGO,u,s} - O^{Ro}_{ZGO,u,s} \right| \le \alpha O^{MAX}_{ZGO,u} \tag{9}$$

3. OPTIMIZATION OF THERMODYNAMIC CYCLE PERFORMANCE IN URBAN MICRO-GRID CHP SYSTEM

More effective energy recovery and utilization imply a reduction in the need for external energy sources, thereby decreasing energy procurement costs. By optimizing energy recovery schemes, microgrids can become more self-sufficient, providing more stable electricity and heat supply, reducing reliance on a single source of energy, and enhancing resource self-sufficiency through waste heat recovery. This paper proposes performance optimization of the recovery scheme for absorption-type CHP systems in urban microgrids. Absorption CHP systems can produce heat while generating electricity, but traditional systems may not fully utilize this aspect. By cascading the recycling and utilization of waste heat, the overall energy utilization efficiency can be significantly improved, and the system can better cope with fluctuations in energy demand. During periods of low energy demand, more energy can be stored; during peak demand periods, this stored energy can be released to meet the demand.

In urban microgrids, absorption CHP systems are efficient facilities that generate both electricity and thermal energy, utilizing waste heat from the traditional power generation process. In the conventional power generation process, the heat generated by fuel combustion is used to produce steam, which then drives a turbine to generate electricity. The key to absorption CHP systems is that they not only generate electricity but also utilize waste heat from the power generation process for building heating, hot water supply, or industrial processes. Absorption CHP systems typically use absorption chillers to utilize waste heat. Unlike traditional CHP systems that use waste heat boilers to generate steam, these systems use thermal energy directly through chemical processes for cooling and heating. Figure 3 shows the structure of an urban microgrid absorption CHP system.

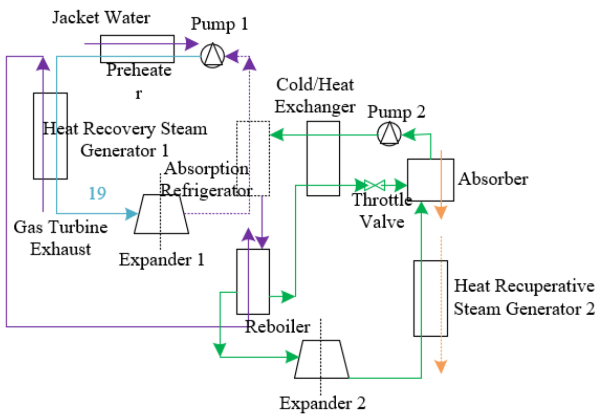


Figure 3. Structure of absorption CHP system in urban microgrids

In the thermodynamic cycle of a CHP system, a high-temperature heat source is first used to generate electricity. Then, there is typically a waste heat recovery unit to capture the heat energy not converted into electrical energy during the power generation process. This heat energy can be directly used for heating or further used in a refrigeration cycle. In the power cycle, the generating units convert the chemical energy of the fuel into electrical energy. During this process, a part of the thermal energy is transformed into mechanical energy, which is then converted into electrical energy. The unconverted thermal energy is usually carried away by cooling water or exhaust. To maximize the energy utilization of the system, this paper will adopt a cascaded energy utilization approach, that is, using heat of different grades in a hierarchical manner. In the constructed cascading system, the highest-grade heat is used for power production, the next highest for heating and industrial thermal demands, and the lower-grade heat can be used for absorption refrigeration or other low-temperature heat applications.

In a CHP system, the role of the turbine is to convert the energy of high-temperature, high-pressure steam into mechanical energy, which is then converted into electrical energy by a connected generator. To calculate the electricity generated by the turbine, several key parameters are needed: the amount of steam or hot gas received by the turbine, the energy content of these steams, the energy conversion efficiency of the turbine, and the efficiency of the generator. In simple terms, we first need to estimate the energy that the turbine can utilize, then multiply it by the turbine's conversion efficiency and the generator's efficiency, to determine the electricity generated by the turbine. Assuming the subscripts for expander, generator, evaporator, preheater, pump, and generator are represented by s, h, EV, PR, o, GE, respectively. Ammonia and water are represented by VG_3, Q. Inlet, outlet, heat production, and environment are represented by IN, OUT, v, EQ. The following formula provides the calculation for the electricity generated by the turbine:

$$\dot{Q}_{s2} = l_{VG_3}\left(g_2 - g_3\right)\lambda_s\lambda_h \tag{10}$$

For the calculation of the total electricity output, it is necessary to consider all devices within the microgrid that can generate electricity. This includes not only turbine generators but also other renewable energy generation equipment such as solar photovoltaic panels and wind turbines. The electricity generated by each device during the same time period is summed up to obtain the total generated electricity. The formula for this calculation is:

$$\dot{Q}_{TA} = \dot{Q}_{VG_3} + \dot{Q}_q \tag{11}$$

In addition to generating electricity, CHP systems can also produce heat. The calculation of the system's heat output involves all possible heat outputs, including but not limited to the heat generated during the CHP process, the heat captured by the waste heat recovery system, and any additional heat generation equipment. When calculating these heat outputs, the efficiency and output of each heat-producing unit must be assessed, and these values are then accumulated. Also, the heat losses incurred during transmission or conversion processes must be subtracted from the accumulated value to determine the total usable heat output of the system. The formula for this calculation is:

$$W_{EV2} = \dot{l}_3\left(g_4 + g_3\right) \tag{12}$$

Finally, the amount of heat produced needs to be converted to an equivalent amount of electricity so that the total energy output of the system can be evaluated in terms of the same energy unit. This conversion involves the concept of energy equivalence, i.e. a certain amount of heat can be converted into a certain amount of electricity. In practice, there is usually a standard conversion coefficient based on which the amount of heat produced can be converted into an equivalent amount of electricity. Such a conversion allows us to measure and compare the value of heat energy in the form of electrical energy. The formula for calculating the equivalent amount of electricity from heat production is given in the following equation:

$$\dot{Q}_{EQ-z} = \frac{W_{CO}}{ZPO_{rz}} \tag{13}$$

Calculating the total equivalent power output of an urban microgrid absorption CHP system requires first determining all the electrical and thermal energy outputs in the system. This includes the electrical energy generated directly as well as the electrical energy obtained through thermal energy conversion. Subsequently, this electrical and thermal energy needs to be converted into a uniform unit of electrical energy measurement, which is done to enable the output of the system in different modes to be measured and compared in a common way. The total equivalent power output of the system can be calculated by the following equation:

$$\dot{Q}_{FOEQ} = \dot{Q}_{VG_3} + \dot{Q}_q + \dot{Q}_{EQ-z} \tag{14}$$

The primary energy utilization rate of the system refers to the ratio of the actual energy efficiency output of the system to the amount of primary energy consumed by the system. To calculate this indicator, it is necessary to measure the total energy output of the system and then compare this total with the amount of primary energy consumed by the system. The primary energy utilization rate of the system can be obtained through the following formula:

$$ORE = \frac{W_{OUT}}{W_{IN}} = \frac{\dot{Q}_{TO} + W_{EV2}}{W_{PR} + W_{EV1} + \dot{Q}_{O1} + \dot{Q}_{O2}} \tag{15}$$

To assess the overall energy quality of the system, i.e., the effectiveness and losses in the energy conversion process, this paper calculates the system's exergy efficiency. This calculation considers all energy flows in the system, including energy inputs, outputs, and losses during conversion. The calculation formulas are as follows:

$$\lambda_{EX} = \frac{R_{OUT}}{R_{IN}} = \frac{\dot{Q}_{TO} + R_Z}{R_{IN}} \tag{16}$$

$$R_z = \left(\frac{S_0}{S} - 1\right)W_{EV2} \tag{17}$$

In absorption CHP systems, in addition to directly generating electricity, the system also produces a significant amount of heat, which can be used for heating, hot water, or industrial processes. The calculation of the equivalent thermal efficiency requires converting these heat outputs into the consumption of primary energy, so as to compare it with traditional energy systems. The formula for this calculation is:

$$\lambda_{EQ} = \frac{\dot{Q}_{FOEQ} - \dot{Q}_{o1} - \dot{Q}_{o2}}{W_{EV1} + W_{PR}} \tag{18}$$

From the above calculations, it is evident that improving the efficiency of cycle recycling of waste heat in urban microgrid absorption CHP systems often involves improvements to the thermodynamic cycles within the system. This paper enhances the efficiency of thermal energy conversion by introducing an expansion device, such as an expander or expansion valve, into the thermodynamic cycle. The function of the expansion device is to utilize the energy of high-pressure thermal fluids. In traditional thermodynamic cycles, waste heat is typically transferred to the working fluid through a heat exchanger, causing it to vaporize. Then, the high-temperature, high-pressure steam does work as it passes through the expander, converting into mechanical energy, which is finally transformed into electrical energy. Waste heat can originate from the heat-electricity generation process in the CHP system, industrial processes, or other heat sources. The expansion device essentially adds a regenerator to the system. The following formula calculates the energy absorbed by the regenerator:

$$W_{REG} = z_{oh} l_h \left(S_{23} - S_{24} \right) \tag{19}$$

It is noticeable that in the given formula for calculating the primary energy utilization rate *ORE* of the system, the total heat production of the system has increased, and the increased part is the energy released in the regenerator. Then:

$$ORE = \frac{W_{OUT}}{W_{IN}} = \frac{\dot{Q}_{TO} + W_{EV2}}{W_{PR} + W_{EV1} + \dot{Q}_{o1} + \dot{Q}_{o2} + W_{REG}} \tag{20}$$

Similarly, the calculation formula for the system's equivalent thermal efficiency has also been adjusted:

$$\lambda_{EQ} = \frac{\dot{Q}_{TOEQ} - \dot{Q}_{o1} - \dot{Q}_{O2}}{W_{EV1} + W_{PR} + W_{REG}} \tag{21}$$

It can be seen that in scenarios without an expansion device, lower-grade waste heat may not be effectively utilized and is directly emitted into the environment. The use of an expansion device as part of the thermodynamic cycle allows this lower-grade thermal energy to be converted into useful work or electrical energy, ensuring that energy can be cascaded at different temperature levels. By appropriately designing the system, the higher-grade thermal energy can be utilized first, followed by the successive downstream transfer of lower-grade thermal energy, achieving maximized energy utilization.

4. EXPERIMENTAL RESULTS AND ANALYSIS

This paper proposes an energy flow optimization scheduling strategy for urban microgrid CHP systems, which enhances the system's ability to accommodate new energy power by introducing rolling and real-time planning, refining the time scales. Figure 4 lists three different scheduling plans for thermal power units: real-time scheduling plan, rolling scheduling plan, and day-ahead scheduling plan. It is noted that the day-ahead scheduling plan is usually set the day before, based on forecasts of the next day's load and generation conditions. The rolling scheduling plan, on the other hand, is an adjusted plan based on the latest information, updated every few hours, building on the day-ahead schedule. The real-time scheduling plan is adjusted according to the current grid conditions and actual generation, updating every few minutes or even seconds.

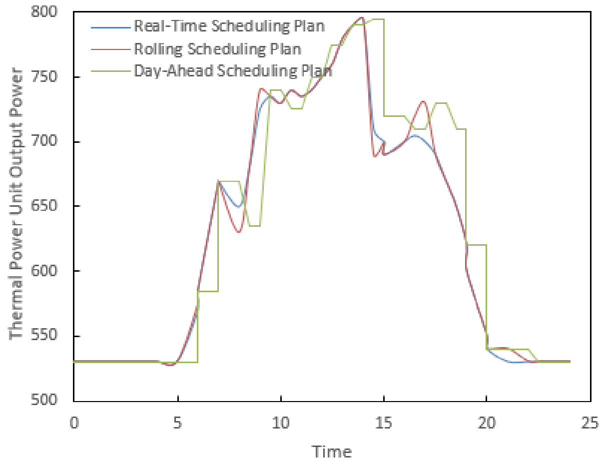


Figure 4. Comparison of output power at different time scales for thermal power units

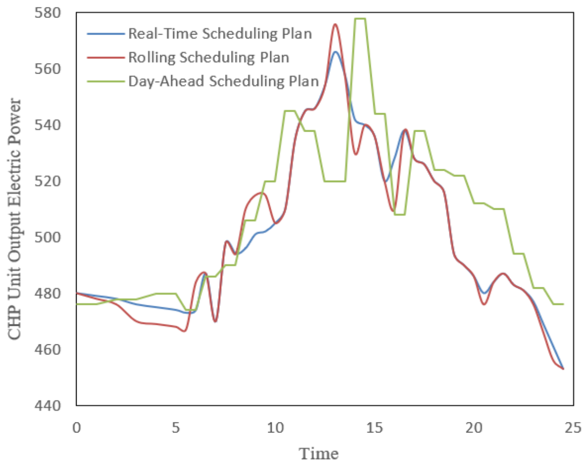


Figure 5. Comparison of output power at different time scales for CHP units

From the figure, it can be observed that before 6 AM, the output power of the three scheduling plans is consistent, indicating that the three strategies anticipate the same power demand for the low-load nighttime period. Between 6 AM and 6 PM, the anticipated power demand gradually increases, reaching a daytime peak. During this period, the real-time and rolling scheduling plans show higher adaptability compared to the day-ahead schedule, more accurately reflecting the immediate load changes and generation conditions, as seen in the adjustments at 6 AM, 7 AM, between 9 AM and 3 PM, and at 5:30 PM. Especially during peak hours (like 1 PM to 3 PM), the real-time and rolling schedules make more adjustments compared to the day-ahead plan, showing greater flexibility in adapting to changes in power demand. After 6 PM, as the load begins to decrease, the power output of all three scheduling plans also starts to decline. During this time, the real-time and rolling plans continue to exhibit higher flexibility and adaptability compared to the day-ahead schedule.

According to Figure 5, the output power of the CHP units under the real-time scheduling plan, the rolling scheduling plan and the day-ahead scheduling plan can be compared to assess the effectiveness of the scheduling strategy. As can be seen from the figure, the real-time and rolling scheduling plans are slightly changed relative to the day-ahead scheduling plan, reflecting the fine-tuning of the actual operating conditions and showing a certain degree of adaptability and flexibility. In the time period from 6:00 to 7:00, the real-time and rolling scheduling plans can better reflect the actual demand, and the adjustments are more frequent and precise compared with the day-ahead scheduling plan. Starting from 08:30, the rolling scheduling plan begins to significantly increase the output power, because it can reflect more accurate predictions or immediate demands. The rolling scheduling plan provides the highest power at 13:00, which is the predicted peak demand. On the other hand, in case of the day-ahead scheduling plan, a power peak appears at 14:00, and this is because it can not predict the specific peak hour. These results indicate that the rolling scheduling plan is more accurate in responding to peak demand. In case of real-time scheduling, the downward adjustment in power at 17:00 is in response to a decrease in actual demand. For all plans, the output power shows a decreasing trend, but the real-time and rolling scheduling makes more refined adjustments, indicating that they can better adapt to decrease in actual demand.

Figure 6 shows the expected output power of the new energy generation units at different hours in a day under three different scheduling plans. Within the study time period, the power variation of the three schedules is not much, but the real-time and rolling schedules show a large increase at 14:00, and then decrease later, indicating the two can better reflect fluctuations of new energy generation in the short term. During 6:00-7:30, the real-time and rolling scheduling plans adjust the generation power more actively, and this is a reflection of the expected increase of solar generation after sunrise. At 14:00, compared with the day-ahead scheduling plan, the real-time and rolling scheduling plans decrease a bit, this is a reflection of the adjustment caused by weather or the changes in new energy generation prediction. After that, since 16:00, the real-time scheduling plan rises again, showing a response to real-time conditions, while the day-ahead scheduling plan remains unchanged at that time. All scheduling plans are relatively stable during the evening hours, but the real-time and rolling scheduling plans show a larger power output between 21:30 and 22:30, due to an increase in wind generation or the optimization of other new energy generation.

From the above analysis, it can be concluded that real-time and rolling schedules offer more flexible and dynamic power adjustments, better accommodating the uncertainties of renewable energy generation, especially during significant changes in the power output of renewable sources like solar and wind energy. The scheduling strategies proposed in this paper, by refining time scales and introducing dynamic adjustments, help enhance the system's adaptability to fluctuations in renewable energy power, ensuring grid stability and maximizing the utilization of renewable energy sources.

From the data in Figure 7, the values of the real-time generation plan are in perfect agreement with the daily load data throughout the 24-hour cycle. This means that the real-time generation plan can accurately track the predicted daily load demand without any deviation. It can be seen that, the real-time generation plan achieves a perfect match with the actual or predicted load demand, and this proves that the scheduling strategy is highly efficient in terms of accuracy, which is very important for gird operation and it means a good balance between power supply and demand. Such consistency also demonstrates that the real-time scheduling system has the ability to respond quickly to load changes, and this is a particularly important feature for new energy generation, because the output of new energy sources is often affected by environmental factors, so the real-time scheduling system must be able to adapt quickly to these changes. Moreover, this consistency also reflects the use of advanced prediction models, these models can accurately predict the daily load demand, which is important for effective integrating the new energy sources, which often have high uncertainties. Via adjusting production schedule in real time to match with load demand, system operators can maintain grid stability, reduce waste, minimize the need to activate backup, or adjust peak use hours of generation resources. In summary, the real-time new energy generation schedule performs excellently in the task of tracking daily load profile data, indicating that the proposed scheduling strategy is very effective in balancing between supply and demand in the power system.

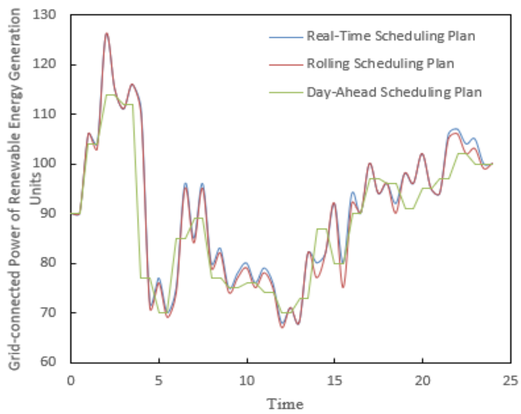


Figure 6. Comparison of output power at different time scales for new energy generation units

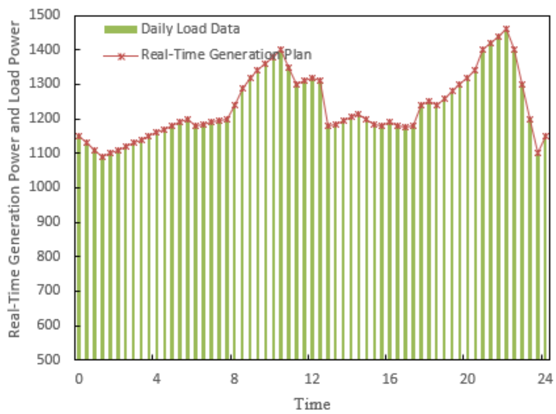
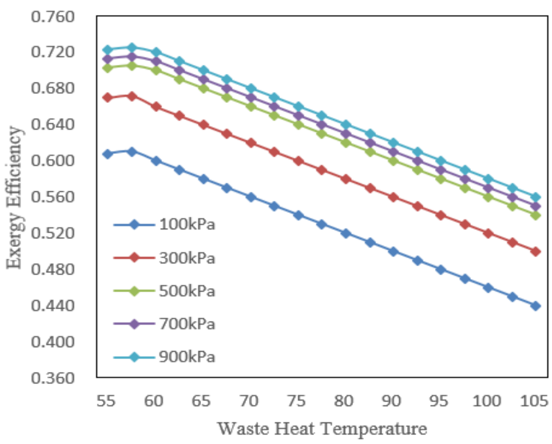
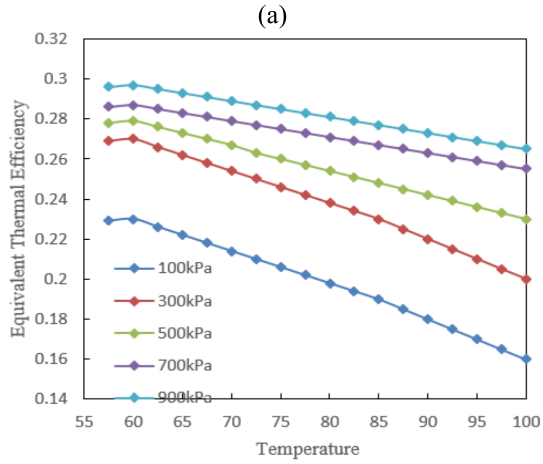


Figure 7. Load-tracking curve of real-time new energy generation plan

Figure 8 illustrates the case of the waste heat recovery system with equivalent thermal efficiency at different waste heat temperatures and evaporation pressures. The yield efficiency is a measure of the performance of a thermal system, which is based on the second law analysis and is related to the quality of the energy. A high exergy efficiency means less energy loss and thus a higher energy utilization of the system. From Figure 8(a), it can be seen that when the evaporation pressure is fixed, the energy efficiency gradually decreases as the temperature of the waste heat increases. This indicates that at higher temperatures, the quality of the waste heat decreases and the system is not able to utilize this thermal energy efficiently. At the same waste heat temperature, with the rise of evaporation pressure, exergy efficiency increases, which is because at higher pressures, the vapor's quality is higher, so it can be converted into energy more efficiently. Data show that, by adjusting the evaporation pressure, the utilization of waste heat can be optimized. In case of lower waste heat temperatures, even at lower evaporation pressures, a relatively high exergy efficiency can be achieved. In case of higher waste heat temperatures, increasing evaporation pressure can compensate for the decrement in exergy efficiency to some extent. According to Figure 8(b), it's known that, under a same evaporation pressure, in most cases, the equivalent thermal efficiency presents a downward trend, this is because as temperature rises, the quality of the thermal energy decreases, and the system's ability to convert this thermal energy into useful energy weakens. For any given temperature of waste heat, the equivalent thermal efficiency tends to increase with the rise of evaporation pressure. This indicates that at higher pressures, the system's ability to utilize waste heat is enhanced because of the corresponding increase in vapor quality and energy level of the working fluid. By appropriately adjusting the evaporation pressure, the equivalent thermal efficiency can be optimized for a specific waste heat temperature, achieving graded recycling and thus improving the overall efficiency of waste heat use.



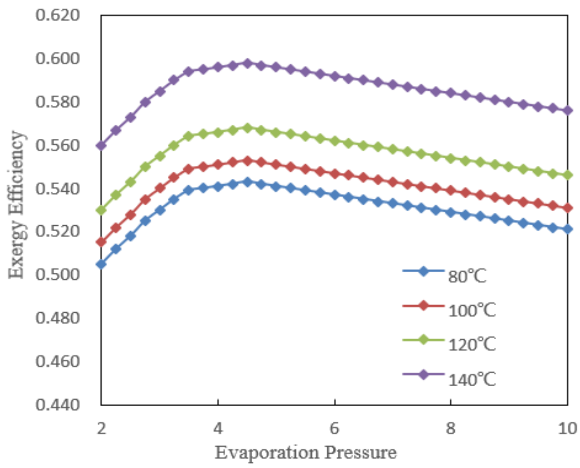
(a)



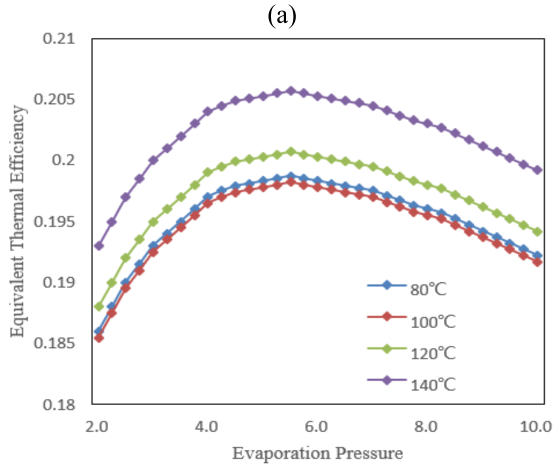
(b)

Figure 8. Exergy efficiency and equivalent thermal efficiency of waste heat recovery systems at different waste heat temperatures

Based on above analysis, it can be concluded that, in order to optimize the thermal cycle performance of the absorption CHP system in urban microgrids, the evaporation pressure can be adjusted to adapt to different waste heat temperatures, and to enhance the system's exergy efficiency and equivalent thermal efficiency. Such cascaded recycling and utilization strategy has effectively improved the energy utilization of the system, ensured reasonable distribution of power and heat, and reduced energy losses. Therefore, the proposed strategy, namely to optimize thermal cycle performance by adjusting the evaporation pressure, is effective. This optimization can significantly increase the equivalent thermal efficiency of the waste heat recovery system, which in turn can improve the energy utilization of the entire CHP system, ensuring reasonable energy distribution, and can help reduce energy consumption and operating costs.



(a)



(b)

Figure 9. Exergy efficiency and equivalent thermal efficiency of waste heat recovery systems at different evaporation pressures

Figure 9 illustrates the exergy efficiency and equivalent thermal efficiency of waste heat recovery systems at different evaporation pressures and heat exchange temperatures of the expansion machine. From Figure 9(a), it can be observed that, for a given heat exchange temperature of the expansion machine, as the evaporation pressure increases, the exergy efficiency gradually improves, reaching a peak, and then slightly decreases.

This indicates that there is an optimal range of evaporation pressure, which can maximize the exergy efficiency, and this optimal pressure is determined by the temperature at which the heat exchange occurs in the expander. Under a same evaporation pressure, which the rise of this temperature, the system's exergy efficiency increases as well, this is because a higher heat exchange temperature can improve the quality of the waste heat source, which enables the system to more effectively make use of this heat for work production. By adjusting evaporation pressure and controlling the heat exchange temperature of the expander, an optimal operating point can be found to maximize the work efficiency and achieve more effective waste heat recovery. According to Figure 9(b), in case of each given heat exchanger temperature of the expander, with the rise of evaporation pressure, the equivalent thermal efficiency first increases, and decreases slowly after reaching a peak, and this indicates that for each set temperature, there is an optimal evaporation pressure that can maximize the equivalent thermal efficiency. In case of a fixed evaporation pressure, with the rise of the heat exchange temperature of expander, the equivalent thermal efficiency would increase in most cases. A higher heat exchange temperature can yield high quality of thermal energy, thereby enabling the system to make better and more effective use of the thermal energy. Data show that, via adjusting evaporation pressure and heat exchange temperature, an optimal operating point for increasing equivalent thermal efficiency can be found, thereby realizing more efficient recovery of the waste heat.

Again, in summary, by optimizing the thermal cycle performance of the waste heat recovery system, this study has effectively improved exergy efficiency and equivalent thermal efficiency; by selecting suitable evaporation pressure and heat exchange temperature of the expander, the energy recovery efficiency of the system has been significantly improved as well. This optimization strategy is proved to be very effective in enhancing the overall performance of the waste heat recovery system, which is meaningful for improving energy use efficiency, reducing energy consumption, and lowering operating costs.

Table 1 compares the data of the performance of the CHP system before and after performance optimization, indicators include performance parameters such as power output, heat production, maximum equivalent power output, expander outlet dryness, and system thermal efficiency, and the effectiveness of the performance optimization of the thermal cycle can be evaluated by analyzing the data of these indicators. As can be seen from the table, after optimization, the system's power output increases from 4456 to 5124, which indicates that the optimization has resulted in a significant increase in power output. After optimization, the system's heat output increases from 3247 to 4789, reflecting higher heat recovery efficiency and utilization. The maximum equivalent power output of the system before optimization is slightly higher than that after the optimization, data is 5148 vs. 5123, meaning that under highest load conditions, the design of the original system is better in terms of electrical energy conversion efficiency. Again, after optimization, the outlet dryness of expander reaches 1, which means that the steam is completely dried, and the operation efficiency and safety of the expander have been improved. The system's thermal efficiency decreases slightly from 22.3% before optimization to 21.36% after optimization, and this decline means that the optimized system will focus more on the power and heat output, not just on thermal efficiency.

In conclusion, performance optimization has significantly increased the electric and heat output of the CHP system, aligning it better with comprehensive energy utilization and market demands. Although there is a slight decrease in the maximum equivalent electric output and system thermal efficiency, the overall energy utilization efficiency of the optimized system is higher. Considering the combined production of electricity and heat, this trade-off is reasonable. The improvement in the dryness fraction at the expansion machine outlet positively impacts system stability and efficiency. While the maximum equivalent electric output has slightly decreased, it can be compensated for by the higher electricity and heat production of the optimized system.

Table 1. Performance comparison of the CHP system before and after optimization

Performance Parameters	Original CHP System	Absorption CHP System System with Expansion Device
Electric Output	4456	5124
Heat Output	3247	4789
Maximum Equivalent Electric Output	5148	5123
Expansion Machine Outlet Dryness	0.8156	1
System Thermal Efficiency	22.3%	21.36%

5. CONCLUSION

This study focuses on energy flow optimization and thermal cycle performance improvement in absorption CHP systems within urban microgrids. Through comparative analyses of real-time scheduling plans, rolling scheduling plans, and day-ahead scheduling plans, as well as an analysis of the exergy efficiency and equivalent thermal efficiency under different waste heat temperatures and evaporation pressures, the study presents a performance comparison of the CHP system before and after optimization.

Experimental results demonstrate that the introduction of real-time and rolling scheduling plans to refine the time scale has enhanced the CHP system's capability to accommodate renewable energy power generation in urban microgrids. This scheduling strategy allows flexible adjustment of the output power of gas turbine units at various time scales, particularly during periods of significant load fluctuations, such as the morning and evening peak hours. Such adjustments contribute to improving energy utilization efficiency and grid stability. Additionally, by optimizing the thermal cycle of the absorption CHP system, a cascading utilization of waste heat has been achieved. This optimization, accomplished by adjusting evaporation pressures and heat exchange temperatures, effectively elevates the system's exergy efficiency and equivalent thermal efficiency. The results indicate that the optimization measures enable the system to maintain high energy recovery efficiency under different operating conditions, reducing energy losses. Experimental findings reveal that the optimized CHP system has increased both electric and heat outputs, indicating an overall enhancement in energy conversion efficiency. Despite a slight reduction in the system's thermal efficiency, from a holistic perspective of energy utilization and comprehensive output, this decline is acceptable, especially when considering that the total production of electricity and heat better aligns with comprehensive energy utilization and market demands. The optimization strategy outlined in this paper not only enhances the production of electricity and heat but also improves system stability and safety through the enhancement of expansion machine outlet dryness. While there is a minor decrease in the maximum equivalent electric output, this can be offset by the higher electricity and heat production of the optimized system.

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