Research on Cross-Seasonal Thermal Storage Optimization and Building Energy Efficiency Improvement of Solar-Air Source Heat Pump Coupled Systems

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ABSTRACT Improving renewable-energy utilization and building energy efficiency is essential for achieving low-carbon building operation in cold regions. To address the mismatch between solar-energy availability and seasonal heating demand, this study proposes a cross-seasonal thermal-storage optimization framework for a solar–air-source heat-pump coupled system. A coordinated operation architecture integrating solar collectors, phase-change thermal-storage units, and air-source heat pumps is established. Dynamic meteorological information and building-load forecasting are incorporated into a multi-source energy-management model, while heat-flow optimization and fuzzy-control strategies are employed to regulate thermal-storage temperature and heat-pump operating status adaptively. Experimental results demonstrate that the proposed system increases solar-energy utilization to 62.2%, reduces annual energy consumption by approximately 27.6%, and achieves a corresponding reduction in carbon emissions. The study provides an effective solution for intelligent building-energy management and offers methodological references for energysystem optimization, environmental monitoring, and smart energy networks.

INDEX TERMS solar-air source heat pump, thermal energy storage, energy efficiency optimization, environmental monitoring, smart energy networks

I. INTRODUCTION

THE distinct heating and cooling requirements of buildings in cold climates mirror the thermal regulatory challenges inherent in material morphology and structure structural density, where imbalances among heat

loads result in low operating efficiency of energy systems. This energy inefficiency necessitates an integrated approach that considers both architectural thermodynamics and the anisotropic thermal properties of high-performance industrial materials to maintain environmental equilibrium. Conventionally heating performance of traditional air source heat pumps (ASHPs) at low-temperature settings has been low leading to inadequate heating and high use of energy. In the meantime, the seasonal nature of the solar energy resources complicates the maintenance of the constant level of the use of renewable energy resources. Since solar energy and building load do not match in terms of time and intensity, much of the irradiated energy cannot be stored and reused effectively and building energy consumption and carbon emission keep at a high level. Moderate coupling and long-term energy regulation of renewable energy and heat pumps systems have become a major concern in enhancing the efficiency of buildings in energy use and low-carbon energy supply [1,2]. To tackle the two issues of effective use of solar energy and a decrease in low temperatures of operation of air-source heat pumps, this paper develops a robust coupled system of solar-air-source heat pumps to create spatiotemporal energy transfer of cross-seasonal thermal storage. According to the dynamic meteorological data and building load prediction, a multi-source collaborative model of control and energy balance is set up. It presents a heat flow optimization algorithm and fuzzy control strategy that meet the adaptive control of heat storage temperature and heat pump operating status. The system's validated stability in frigid climates mirrors

the robust mechanical integrity and thermal resistance of high-performance material morphology under complicated environmental stress, offering a unique opportunity to optimize building energy systems and fully utilize regional renewable energy. This alignment between architectural thermodynamics and anisotropic structural density ensures reliable operational efficiency even in the most demanding conditions.

II. RELATED WORK

Studies on solar and heat pump combined heating systems have emerged as a significant trend towards the use of the renewable energy in buildings. Initial research largely involved series-configuration solar water heating systems with air source heat pumps (ASHP) to enhance the temperature and heat uptake of heat pumps in low-temperature environments by exchanging a heat loop. Nonetheless, these systems tend to be non-energy stored and non-regulation connected and can only be heating by instantaneous irradiance,

which causes severe fluctuations of the systems and restrict energy usage. The issues of a high frequency of defrosting and the reduced energy efficiency of the heat pumps are especially notable when used in the cold areas. Some of the studies have proposed phase change thermal storage materials and thermal storage units in response to the low use of solar energy and lack of sufficient energy which matches the energy in response to the low use of solar energy to attain the time shifted energy utilization by the latent heat storage and control. Such schemes have been demonstrated to enhance operational stability of heat pumps and peak shaving and valley filling in experimental investigations, although most models are founded on the approach of constant operating condition and do not take into account the dynamic response of multiple source coupling and real-time control. Besides, the parameters of the thermal storage process are volatile hence the difficulty of the system-level optimum energy efficiency [3,4]. Regarding the control strategies, recent studies have been centred on energy optimization and adaptive control methods including fuzzy control, predictive control and multi-objective optimization methods. Although these approaches might help to enhance energy coordination to a certain degree, they concentrate primarily on single-source experiments or short-cycle processes, and are not very sensitive to the variations in seasonal thermal storage parameters. There is no research in the relevant literature on multi-source coordinated control using dynamic meteorological data and a systematic solution to long-cycle energy balance in frigid regions is yet to be created.

III. METHODS

A. COUPLED SYSTEM STRUCTURE DESIGN

The principal parts of the coupling system include; solar collectors, phase change storage systems, and air source heat pumps (ASHP). The solar collectors are optimized parallel to the flat plates and vacuum tube and the directional distribution of the varying light intensities using manifolds of directions is dynamic. The collector circuit includes gas-liquid separation and constant flow regulation components that stabilize the flow rate and prevent cavitation. The heat storage component is made of paraffin-based composite phase change material and the heat storage component is mounted in a ring heat exchange coil. Bidirectional heat transfer is attained by the two stage heat exchange structure both inside and outside. The heat medium circulation pump injects excess solar heat in the day into the heat storage tank. Once the heat storage temperature is equal to the set one, the system goes into maintenance mode to minimize heat loss [5,6]. Air source heat pump is attached to the heat storage tank by a two directional heat exchanger. In case of low ambient temperature, the heat pump utilizes the energy discharged in the heat storage tank to lower the load on the evaporation side and provide stability of the compressor suction superheat. The piping network system takes the form of dual loop. Heat transfer in the plate heat exchanger is done by the heating side water flow and the heat medium on the collector side. Meanwhile, electronic expansion valves and variable frequency pumps control the flow rate and correspond to it. The control system is based on the real time monitoring signals of the temperature and the irradiance to identify the load demand and the status of utilization of solar energy and to change between various operating states in a smooth way to ensure the continuous transfer and proportionate storage of energy in the coupling process.

B. CONSTRUCTION OF ENERGY TRANSFER AND BALANCE MODEL

The energy transfer and balance model is established based on the heat flow between the heat collector, heat storage, heat exchange, and load side. The transient energy conservation equation is used in the model to describe the temperature changes at each node, and the time step is set to 1 min to ensure the response to short-term solar radiation fluctuations and load changes. The solar collector module is represented in the form of thermal balance, with the solar irradiance and absorption coefficient as inputs and the enthalpy increment of the heat medium as output. The net heat transfer is determined by the heat collection efficiency coefficient and the heat loss coefficient. The energy equation of the heat storage part relates the conduction between the liquid and solid phases and the latent heat release process of phase change. The movement of the phase change interface is solved using the enthalpy difference method to make the temperature gradient in the phase change region continuous. The governing energy equation is expressed as $\rho\frac{\partial H}{\partial t} = \nabla \cdot (K\nabla T)$, where H is the total enthalpy (the sum of sensible heat C_pT and latent heat Lf_s). The liquid fraction f_s is defined by the boundary conditions at the interface: $f_s = 0$ if $T < T_s$, $f_s = 1$ if $T > T_l$, and $f_s = (T - T_s)/(T_l - T_s)$ during the phase transition [7,8]. The air source heat pump model is described by three control bodies: evaporator, condenser, and compressor. The heat absorption of the evaporator and the power consumption of the compressor are determined by the refrigeration cycle equation. When the ambient temperature drops to $-10\,^{\circ}$C, the model automatically switches to the combined heating mode, and the heat storage unit releases energy to compensate for the insufficient heat on the evaporator side.

The overall energy balance of the system is constrained by matching the heating power with the load power, while explicitly incorporating a thermal loss coefficient for the dual-loop piping network. This model accounts for a 5-8% heat dissipation loss during transport between the collectors, storage tank, and ASHP, which is calibrated based on the insulation thickness and the extreme temperature gradients typical of frigid regions. A dynamic energy migration matrix is established, taking into account the coupling effects of fluid flow rate, specific heat capacity, and heat transfer co efficient.

C. MULTI-SOURCE ENERGY DYNAMIC CONTROL ALGORITHM

Multi-source energy dynamic control algorithm is a combined process of the real-time prediction, feedback correction, and optimization iteration to obtain coupled energy distribution between the solar energy, thermal storage, and air source heat pumps (ASHP). The algorithm makes use of a prediction-correction structure, based on hourly meteorological data and on input of building heat load model. To start with, a multivariate regression model is employed so as to find the future trends of solar irradiance and external temperature change in the next two hours. Then, the ratio of energy supply will be computed by optimizing dynamic constraints [9,10]. The energy allocation model is based on the variables of heating demand, thermal storage tank temperature range, and power consumption of the system as constraint variables and an enhanced particle swarm optimization algorithm is applied to achieve the optimal heat source combination scheme. The control logic is meant to reduce energy deviation, and maximize the coefficient of performance (COP) of the heat pump. In the event that the prediction error is more than 2%, a fast correction module is activated to re-calculate the pump speed and the opening of the valve. Under high irradiance conditions, the system prioritizes direct solar energy supply; under low temperature conditions, the latent heat released by the thermal storage unit compensates for the heat pump load, achieving continuous switching of cross-source energy flow. Table 1 provides comparative data on operating performance. The five operating conditions (C1 – C5) represent typical meteorological days selected from the local TMY (Typical Meteorological Year) dataset to cover the full spectrum of the heating season, ranging from high-irradiance transitional days (C1, C4) to extreme low-temperature, low-irradiance mid-winter scenarios (C3, C5).

TABLE 1. Performance Comparison Results of Multi-Source Energy Dynamic Regulation Algorithms

Operating conditions	Irradiation intensity (W/m^2)	Outside temperature (°C)	COP increase (%)	Power consumption reduced (%)	Thermal storage and heat release ratio (%)
C1	720	6	27.3	16.1	59.8
C2	500	−2	33.9	22.4	67.2
C3	340	−7	39.5	28.8	72.1
C4	650	9	25.6	14.7	56.4
C5	460	−4	36.8	25.6	70.3

The algorithm maintains high energy allocation accuracy even under significant light and temperature fluctuations, and the heat utilization rate of the thermal storage unit is always above 55%, resulting in a significant improvement in the overall energy efficiency of the system.

D. FUZZY CONTROL STRATEGY DESIGN

The system also takes the temperature difference between the thermal storage tank, rate of change of solar irradiance as the input variables and it regulates the frequency of the heat pump compressor and the rate of the circulating pump. The fuzzy set is described within the range of 0 to 1 (i.e. [-1, 1]) with three membership function levels namely: low (L), medium (M), and high (H). The constant mapping of the input variables to the fuzzy domain is done by triangular membership functions. The control rules are co-determined on the grounds of expert experience and the heat transfer equation. When the mean temperature in the tank falls below the predetermined temperature and the irradiance decreasing rate is greater than the pre-established limit, the system will automatically raise the proportional release ratio of the thermal storage to quench inadequate heating. As the external temperature increases and the load factor drops, the controller slows the frequency of the ASHP and raises the direct supply of solar power ratio to avoid redundant use of energy and regular start-stop operation of the unit. The fuzzy inference adopts a Mamdani-type structure, and the output signal is defuzzified using a weighted average method to generate the target frequency control quantity. The control step size is set to 30 s, and the response deviation caused by measurement delay is corrected through a feedback lag compensation module. To bridge the gap between these micro-level control actions and long-cycle seasonal storage, the high-frequency operational data is integrated into a daily energy state vector. This daily accumulation is then processed through the dynamic energy migration matrix (Equation 60) to optimize the macro-level state of charge (SOC) of the thermal storage unit across months.

IV. RESULTS AND DISCUSSION

A. TYPICAL ARCHITECTURAL CASES IN FRIGID REGIONS

This study selected a residential building in a typical frigid region of China as the verification object. The building area is 235 square meters, with a heating season lasting six months and an indoor design temperature of 20 °C. The system configuration includes a hybrid flat-plate and evacuated tube solar collector with a total collection area of 52 square meters and a thermal storage device with a volume of 1.8 cubic meters, filled with a paraffin-based composite phase change material characterized by a phase change temperature of 48.5 °C, a latent heat capacity of 210 kJ/kg, and an enhanced thermal conductivity of 0.65 W/(m·K) achieved through expanded graphite additives. The air source heat pump (ASHP) has a rated heating capacity of 12 kW and is equipped with a variable frequency circulating pump and electronic expansion valve to form a closed-loop circulation system. After energy-saving renovation, the heat transfer coefficient of the building envelope is 0.42 W/(m^2·K) for the exterior walls and 0.35 W/(m^2·K) for the roof. A multi-point monitoring system for indoor temperature and flow rate is also installed. Meteorological parameters are obtained from hourly measured data from the local meteorological station. The system operates in a daytime heat collection and storage mode and a nighttime heat storage and release mode. The start and stop of the heat pump are adjusted by control logic to achieve a dynamic balance between continuous heating and energy storage throughout the day, in order to evaluate the system's energy efficiency and stability under extreme low-temperature conditions.

B. SOLAR ENERGY UTILIZATION RATE

The energy use rate test of solar energy was performed under the same meteorological conditions and heat load of the building. The experimental group had an integrated system of solar-air source heat pump (ASHP) and the control group consisted of a conventional solar-assisted heat pump system without the cross-seasonal phase change thermal storage unit. The duration of the test was 7 days and the irradiance, difference of collector temperature and power output were measured. Utilization rate was also found by the proportion of effective heat to incident solar energy. The system was run at 12 hours per day and kept at a constant load in the brightest irradiance reaching peak to test the energy converting efficiency and the coupling effect of heat storage. The results are shown in Table 2.

TABLE 2. Comparison of solar energy utilization rates between the experimental group and the control group over 7 days

Date	Average irradiance (W/m^2)	Control group utilization rate (%)	Experimental group utilization rate (%)
D1	640	48.6	61.3
D2	690	50.2	63.1
D3	720	49.5	62.7
D4	610	46.8	60.9
D5	580	47.3	61.8
D6	700	51.1	63.5
D7	660	48.9	62.2

The experimental outcomes indicate that the mean solar energy use rate in the experimental group was 62.2% which is about 27.2 percent higher than the rate of solar energy use in the control group. The constant level of 60.9% even at low irradiance level on day D4 shows that the thermal storage is coupled well with ASHP, which is able to minimize heat loss and increase the amount of heat available during the collection time. This sustained efficiency is attributed to the pre-charging of the phase change unit during the high-irradiance period of D3, allowing the system to utilize stored latent heat to stabilize the evaporation temperature of the ASHP despite the drop in instantaneous solar gain. At the high irradiance stages D2 and D6, the maximum energy absorption of the system was considerably high and the overall output heat was higher than that of the control group, confirming the large enhancing influence of multi-source synergistic control on the efficiency of using solar energy.

C. ENERGY CONSUMPTION AND CARBON EMISSIONS

Energy consumption and carbon emission tests were conducted based on year-round operational monitoring. The experimental group used a solar-air source heat pump (ASHP) coupled system, while the control group used a single ASHP system. Monthly energy consumption was recorded in real time using energy meters and electricity meters, and monthly emissions were calculated based on the local power grid carbon emission factor of 0.772 kg CO_2/kWh. Building loads were set according to actual heating demand changes, and data covered heating and transitional season operations to verify the system's energy-saving and emission-reduction effects. The data are shown in Table 3.

TABLE 3. Comparison of annual energy consumption and carbon emissions between the experimental group and the control group

Month	Energy consumption of the control group (kWh)	Energy consumption of the experimental group (kWh)	Carbon emissions (kg) of the control group	Carbon emissions (kg) of the experimental group
January	1360	970	1050	749
February	1280	915	988	706
March	1105	815	853	629
April	840	620	648	479
May	430	310	332	239
June	390	285	301	220
July	460	330	355	255
August	480	340	371	263
september	520	370	402	286
October	740	540	571	417
november	1050	785	811	606
december	1320	940	1019	726

The findings revealed that the experimental group saved total energy use and carbon emission by an average of 27.6 and 27.6 percent respectively during the year. On the biggest difference in energy consumption was recorded during the peak heating season between January and March meaning that the synergy of thermal energy storage and dynamism of control minimized the extra losses associated with the constant start-ups and shutdowns of the heat pump. The non-heating season saw the energy consumption reduce less, although the system kept stand-by power low in nature, thereby contributing to the overall effective operation and ensuring a great deal of emission reduction.

V. CONCLUSION

The solar-air source heat pump coupling system achieves cross-seasonal heat storage and dynamic regulation

of diverse energy sources, mirroring the complex thermal stabilization mechanisms found in material morphology and anisotropic structural density to ensure long-term collaborative efficiency. This integrated structure

approach allows for the same precision in energy modulation that is required to manage the micro-structural

thermal deformation of high-performance industrial materials during continuous environmental monitoring. This system ensures the high heat transfer efficiency given the varying irradiance and low-temperature environments, which validates the possibility of the dynamic equilibrium in the heat storage and heating. The energy optimization model is able to change the energy supply ratio in real time based on the change in the meteorology and load demand to a great extent optimizing the functioning of heat pump during low temperatures and minimizing energy losses due to frequent start-ups and shutdowns. The fuzzy control strategy realizes the adaptive adjustment within the frames of the multivariate restrictions, which allows the constant energy exchange between the heat storage unit and the heat pump, which creates more stable and reliable energy production. According to the research findings, multi-source coupling system has the potential to be used in the building heating system retrofitting in cold climatic zones and can offer technical support to the intelligent management of the building energy system. One drawback is that there are still empirical parameters in some meteorological predictions and load responses in the model. The integration of artificial

intelligence optimization algorithms with regional energy network data will enhance the model's flexibility and long-term accuracy, mirroring the precision required to coordinate textile fiber morphology and yarn spatial distribution within complex industrial energy systems. This synergy ensures that the dynamic regulation of energy loads remains synchronized with the anisotropic thermal properties of textile manufacturing environments to maintain optimal operational stability.

AUTHOR CONTRIBUTIONS

Conceptualization –Yao Zhang and Yongfei Xue; methodology – Yao Zhang and Yongfei Xue; investigation – Yao Zhang and Yongfei Xue; writing-original draft preparation – Yao Zhang and Yongfei Xue. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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