Adaptive Model Control of Residential Solar-Air Hybrid Heat Pump Water Heating System

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ABSTRACT

With the increasing adoption of renewable energy in the power grid, the future of building energy systems is transitioning toward a distributed, multi-source energy framework. To significantly alleviate strain on the power grid and enhance the integration of renewable energy sources, it is important to optimize the use of energy storage and leverage the thermal mass of building structures. Notably, heating and cooling needs account for over 30% of a building's energy consumption. To realize decarbonization, this paper proposed a residential solar-air hybrid heat pumps water heating system. An adaptive model predictive control is used to control it performance. An online updated modeling method, based on the simplification of the physical mechanism model and the incorporation of real-time data updates, is adopted to enhance the accuracy and adaptability of the model predictive control, thereby improving optimization outcomes. As a result, the developed model predictive controller consistently demonstrates 17.8% energy saving and 31.9% cost savings when compared to conventional rule-based control strategies.

1.INTRODUCTION

To effectively accomplish the goal of decarbonization within the building sector, a pivotal strategy involves the full electrification of operations coupled with the utilization of renewable energy (*Srinivas et al., 2022*). Given that domestic hot water and space heating constitute a substantial portion of energy consumption in buildings, their transformation must be driven by the integration of heat pumps and renewable energy technologies to realize decarbonization. Enhancing the efficiency of equipment is essential, but equally critical is implementing demand response mechanisms through optimized control systems and system flexibility. Consequently, employing multi-heat source heat pumps and implementing optimal control measures emerges as a technical imperative for achieving energy efficiency and carbon reduction objectives in the realm of building operations.

The air source heat pump, a widely adopted device, efficiently utilizes electricity to generate heat. However, it faces challenges in extreme outdoor conditions, which can be mitigated by integrating solar energy into the system, thereby enhancing its flexibility and sustainability (*Cai et al., 2022*). This study introduces a novel approach featuring a three-fluid heat exchanger to avoid refrigerant distribution issues (*Marinelli et al., 2020 & Zhang et al., 2020*). This innovative design enables simultaneous heat exchange among three fluids and streamlines system architecture while maximizing the utilization of heat exchanger area. Furthermore, by incorporating a heat storage water tank, the system facilitates renewable energy utilization, enhancing its overall efficiency and flexibility.

However, the integration of multiple heat sources introduces complexity into the system, leading to fluctuations in parameters such as heat transfer coefficient and evaporation temperature. Consequently, optimizing system control becomes challenging. Additionally, the modeling of dual-heat source heat pump hot water systems is intricate and lacks a concise yet accurate model to facilitate optimal control strategies.

The current control methods primarily focus on mode switching for dual-heat source heat pumps and system design (*Francesco et al., 2023, Cai et al., 2020, Kong et al.2024 & Qiu et al.2023*). However, due to the challenges in modeling and the high computational complexity associated with dual-heat source heat pumps, achieving effective demand response through real-time optimization control remains elusive. While heat pumps have been modeled by various researchers, these models are not suitable for real-time control. To achieve optimal control of the system and respond to price fluctuations simultaneously, a simple, fast, and accurate model is required. This model should be adaptable to dynamic changes, capable of handling external disturbances, and compliant with specific constraints.

Model Predictive Control (MPC) is a technique utilized to address constrained multi-objective optimization problems and has found extensive application in the construction field (*Ján et al., 2023 & Pergantis et al.*). However, the model of a dual heat pump is subject to constant changes due to external disturbances and system state variations. Consequently, the system's model also undergoes continual adjustments. To tackle the challenge posed by these model changes, Adaptive Model Predictive Control (AMPC) has emerged. AMPC employs adaptive algorithms to dynamically modify the model based on real-time performance, thereby enhancing control efficacy. *Yu et al.,2024* used adaptive building models to improve thermal comfort. *Shiyu Yang et al., 2020* features an adaptive machine-learning-based building dynamics modelling to cut down the model construction time.

This paper proposed a reasonable domestic hot water system in the future scenario and introduced a novel Adaptive Model Predictive Control (AMPC) approach to address the demand response challenges encountered in multi-heat source heat pump systems. By employing an adaptive linear model, the complexity of the problem is simplified, resulting in reduced computational demands. Additionally, an online updated modeling method, based on the simplification of the physical mechanism model and the incorporation of real-time data updates, enhances the accuracy and adaptability of the model predictive control, thereby improving optimization outcomes. Furthermore, a simulation model of the multi-heat source heat pump system is developed, and optimization results are analyzed across different typical days.

2. METHODOLOGY

2.1 System principle

In the foreseeable future, the evolution of domestic hot water systems will pivot towards integrating renewable energy sources and harnessing heat pump technology. To maximize the utilization of renewable energy, this paper proposes a hot water system tailored for household use. Specifically, it suggests employing a three-medium heat exchanger as the evaporator for a multi-heat source heat pump. This heat exchanger comprises an inner tube, an outer tube, and an outer fin. The inner tube functions as the refrigerant flow pathway, while the space between the inner and outer tubes facilitates hot water circulation. Additionally, the outer fin provides a channel for air flow. Such a configuration allows the refrigerant to exchange heat with external air and internal hot water separately or simultaneously. Given that solar radiation primarily heats the hot water, this evaporator design effectively harnesses both solar energy and ambient air as heat sources.

The efficiency of a multi-heat source heat pump is influenced by numerous factors, including the temperature of the solar heat medium, outdoor air temperature, temperature differential between the two media, and the temperature of the hot water tank. These variables render the efficiency model of the water tank complex and not easily expressible in simple terms. Additionally, the selection of operating modes for the dual heat source heat pump is critical. For instance, if valve 1 and valve 3 are opened while the solar radiation panel is open, the hot water directly flows to the hot water tank rather than the evaporator, resulting in the heat pump operating in air source heat pump mode. If valve 2 and valve 4 are opened, resulting in the mulit-resources heat pump mode. The system switches to single air source heat pump mode in the absence of solar radiation or during high outdoor air temperatures. Conversely, when both heat sources are utilized, the system operates in mixed heat source heat pump mode. The cop of multi-heat source heat pump mode is higher than air source heat pump.

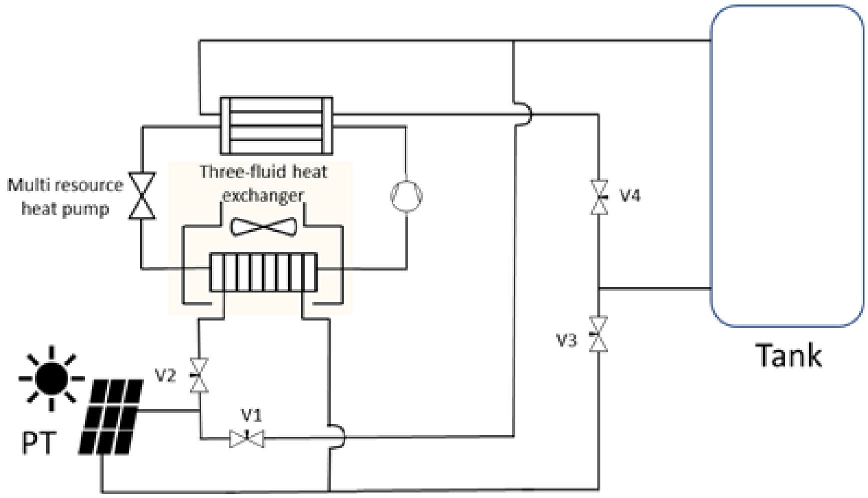

Figure 1 Residential solar-air multi-resource heat pump water heating system

2.2 Simulation of multi-resources heat pump

In this paper, a simulation model of the multi-resource heat pump utilizing a three-fluid heat exchanger is established. The condenser model employs a lumped parameter approach, and the ε-NTU method is utilized for heating calculation. The evaporator, a three-fluid heat exchanger involving multiple fluid heat exchanges, is modeled using the distributed parameter method. Micro-elements are divided along the longitudinal direction of the tube to capture the heat exchange process comprehensively. Heating of refrigerant-air and refrigerant-water, as well as pressure, temperature, and enthalpy of the refrigerant, are calculated along the refrigerant flow direction. The model's validity has been confirmed through experimental verification. The compressor model adopts an isentropic compression speed model. The entire heat pump simulation process is illustrated in **Figure 2**.

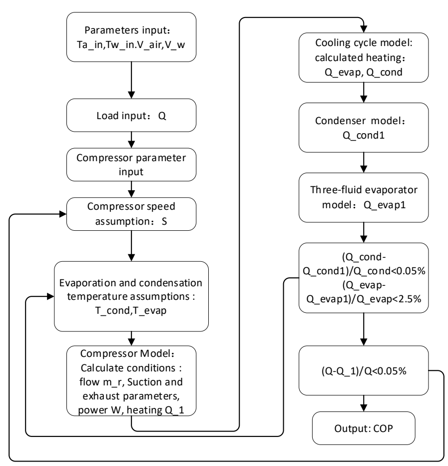

Figure 2 Simulation of the multi-resources heat pump

2.3 Controller design

The system is controlled using the Model Predictive Control (MPC) method, which relies on a predictive model to forecast the next state and output based on an optimal future control sequence. This sequence is computed using a cost function. However, only the initial control action is implemented in the real system. The measured state is then fed back to compensate for prediction errors, and the optimization process is iteratively repeated for continuous improvement. The general framework for MPC (*Zhang et al., 2016*) is described by a finite horizon optimization problem in (1),(2),(3),(4) :

$$J(x_0) = \min_{u_0,\ldots,u_{N-1}} \sum_{k=0}^{N-1} l_k(x_k, u_k, r_k) \quad \text{Cost function} \tag{1}$$

Subject:

$$(x_k, u_k) \in X_k \times U_{c,k} \quad \text{Constraints} \quad (2)$$

$$x_{k+1} = f(x_k, u_k) \quad \text{Prediction model} \quad (3)$$

$$x_0 = x \quad \text{Initial state} \quad (4)$$

Disturbances, such as weather conditions, load, and electricity prices, are predicted to obtain relevant data, which are then fed into the embedded model of the controller. The model is optimized based on the cost function and future predictions, resulting in an optimized output sequence. This sequence is subsequently implemented in the test set, yielding actual COP output data. To ensure the accuracy and adaptability of the model, the parameters of the embedded model are dynamically updated using the least square method.

The tank model with solar collector model and heat pump model is as follows in (5-10):

$$CV\rho \frac{dT}{d\tau} = \delta \cdot Q_{solar} - Q_{loss} + Q_{heat\ pump} - Q_{load} \quad (5)$$

$$Q_{loss} = U \cdot (T_{out} - T) \quad (6)$$

$$Q_{solar} = \eta \cdot I_{solar} \quad (7)$$

$$\eta = 0.74 - 3.65 \frac{T - T_{out}}{I_{solar}} \quad (8)$$

$$Q_{heat\ pump} = P \cdot COP \quad (9)$$

$$COP = aT_{out} + bT + c \quad (10)$$

where the parameters C and ρ denote the specific heat capacity and density of water, respectively, and V represents the volume of water in the tank. The variable Q_{solar} represents the heat collected through the solar collector, and $Q_{heat\ pump}$ represents the heat obtained through the assisted heat pump heater. Q_{load} represents the heat consumed by the end-user; Q_{loss} represents the heat loss to the outdoor environment. where η represents the efficiency of the solar collector, T_{out} is outdoor temperature, and I_{solar} represent solar irradiance.

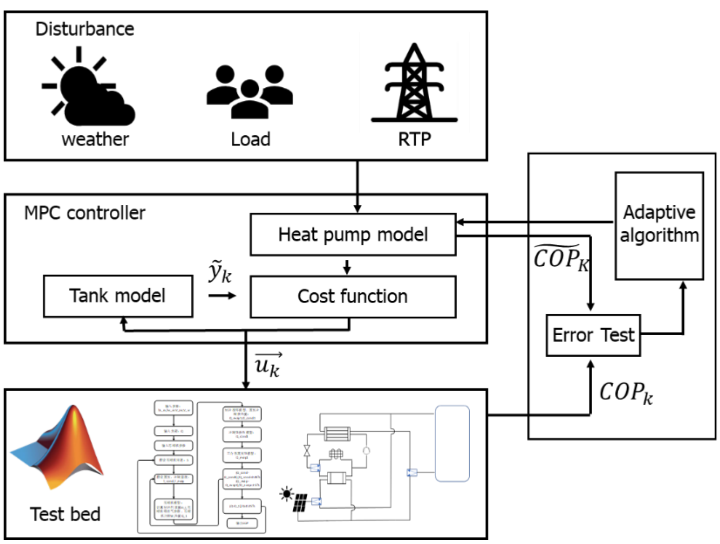

Figure 3 Control frame of adaptive model predictive control

Specifically, the model parameters of the Coefficient of Performance (COP) are subject to real-time changes and are updated adaptively. The water tank model is transformed into a state-space representation, facilitating adaptive updates of its model parameters.

The interior point method is employed for solving the optimization problem, resulting in a series of optimization signals at the predicted level. However, only one signal is applied, after which rolling optimization is conducted. To balance solution time and accuracy while accounting for future external disturbances such as electricity prices, the prediction horizon is set to 30.

Thermostatic Controller: It is similar to a PID controller, this controller maintains a constant temperature control at 40°C.

3. RESULTS

3.1 Disturbance

This paper investigates the application of a multi-source heat pump heating system to provide heat for a large family residing in Beijing. The sizing and fitting parameters of the hot water tank and collector are carefully selected in accordance with local standards. Additionally, modeling of the three-medium heat exchanger is conducted based on actual engineering samples. The heat exchange area and other pertinent parameters are presented in the following **Table 1**.

Table 1 system parameters of multi-resources heat pump domestic hot water heater

System parameters			
Tank volume	500L	Location	Beijing
Plate angle	30°	Heat pump capacity	1000 W
plate area	2.25 m^2	Heat leakage coefficient	1.6 W/K
Heat flow rate	0.6 m^3/h	air mass flow	1000m^3/h

In this study, solar radiation and outdoor temperatures were obtained from the websites of local observatories. Typical winter and summer days in Beijing were selected, and the specific climate data are illustrated in **Figure 4**. The hot water load exhibits predictable characteristics based on human behavior. Since there exists ample literature on building load forecasting, this aspect is not the primary focus of this paper.

The electricity price used in the simulation corresponds to the peak, valley, and flat electricity pricing structure for Chinese residents, as depicted in the **Figure 5**.

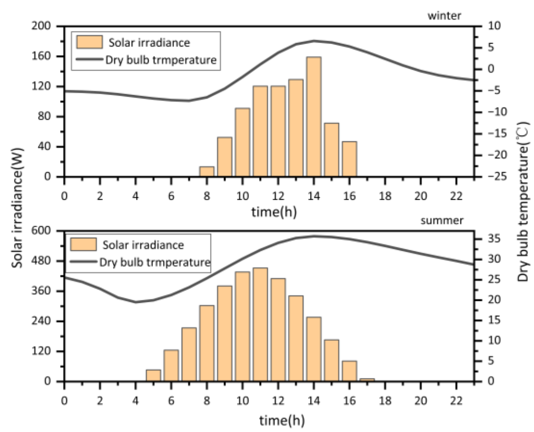

Figure 4 Typical daily weather conditions in Beijing

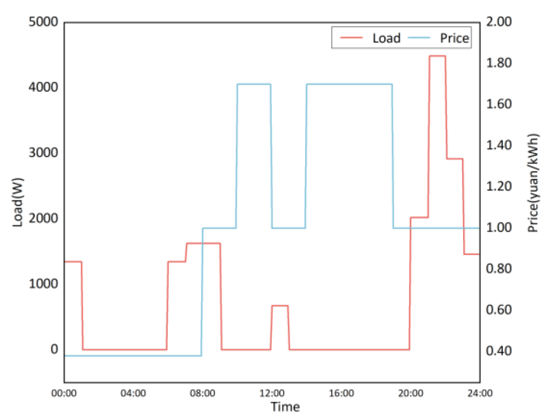

Figure 5 Load and electrovalence

As a result, all parameters and disturbance of the system was established. It is assumed that all forecasts are precise and there is no uncertainty. Additionally, the controller's design must satisfy the end user's load requirements, optimize costs, and facilitate demand response.

3.2 Results and analysis

The heat pump heating output and water tank temperature variation were generated by running two controllers on the typical day. **Figure 6** and **Figure 7** illustrates the trends observed during the typical day.

AMPC optimizes energy output in advance during the period of lowest electricity prices, typically between 0:00 and 8:00. Additionally, it preheats the water tank, effectively managing peak loads and significantly reducing costs. However, the rise in condensation temperature resulting from the increased tank temperature leads to a decrease in COP. The AMPC demonstrates greater sensitivity to COP variations, adjusting in real time. Despite an anticipated COP increase between 10:00 and 14:00 due to rising outdoor temperatures, the COP prediction of AMPC shows less correlation with outdoor temperature, emphasizing the influence of tank temperature. Consequently, AMPC exhibits reduced heat output during the day. This leads to a notable decrease in tank temperature and a significant COP increase. This dynamic enables more efficient heat input, thereby reducing energy consumption and costs. Moreover, the heat dissipation from the tank also rise by the tank temperature. Winter exacerbates this issue, as low outdoor temperatures result in higher heat dissipation ratios. This, in turn, causes AMPC to consume more power, particularly in certain weather conditions.

Traditionally, thermostatic controllers maintain temperatures at the preset levels, minimizing heat dissipation. However, variations in COP challenge the assumption that thermostats always consume the least energy. AMPC which equipped with precise COP predictions and adjustments within the human comfort range, operates below the set temperature by a certain margin, thereby consuming less power compared to a traditional thermostat. During specific peak load periods, AMPC strategically lowers the tank temperature below the preset value, while still maintaining comfort within the acceptable range. This action not only reduces energy consumption but also enhances COP, thereby making AMPC both cost-effective and energy-efficient, particularly during summer months when the heat dissipation ratio is minimal.

In summary, AMPC demonstrated the most superior performance across typical working conditions which shown in **Figure 7** and **Figure 8**, achieving cost savings of 24% -32% compared to thermostats controller.

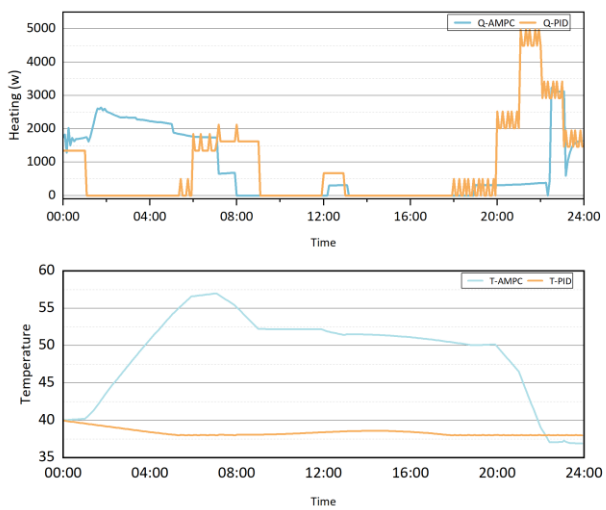

Figure 5 Time series control results of typical winter day

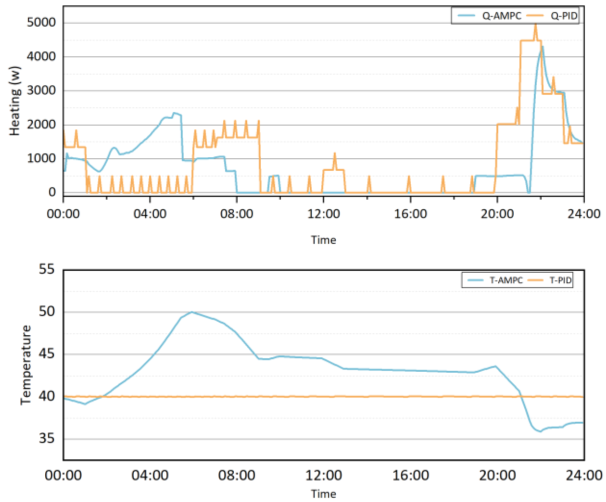

Figure 6 Time series control results of typical winter day

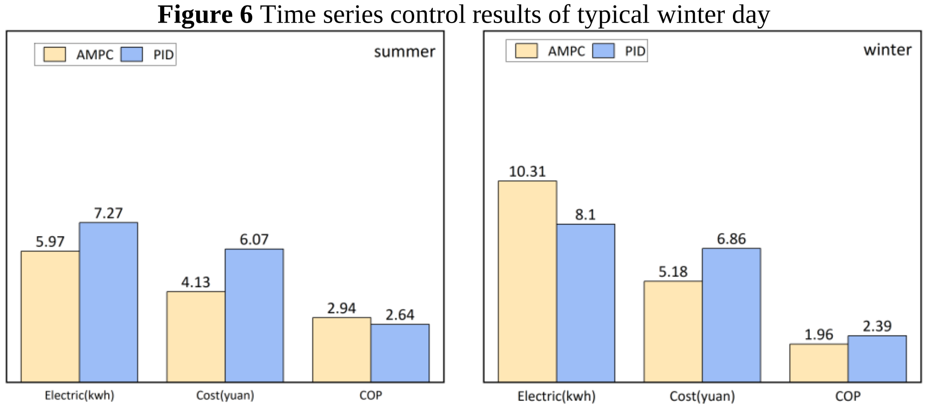

Figure 7 Performance under different controller of typical day

4. CONCLUSIONS

In consideration of the anticipated hot water demand of residential buildings in the future, alongside the imperative of energy efficiency and carbon reduction, this paper introduced a multi-source heat pump hot water system. It simplified the system structure and enhance efficiency with the utilization of renewable energy. Nevertheless, controlling the multi-source heat pump system is challenging due to its susceptibility to disturbance changes. Despite previous studies on multi-source heat pumps, a straightforward and efficient control method for the multi-source heat pumps to achieve optimal system demand response remains notably absent. This study aims to bridge this gap by employing a simplified model to accurately describe the multi-source heat pump and implementing AMPC to achieve demand response under peak-valley flat pricing. The proposed AMPC dynamically updates the COP function based on the embedded model and actual error, ensuring effective and adaptive control of the system.

This study rigorously examined the performance of two control methods across two typical weather conditions. The study's conclusions are as follows:

- AMPC emerged as the standout performer across both typical operational scenarios, delivering substantial savings of 24% to 32% in operating costs compared to thermostatic control.
- AMPC distinguished itself as the preeminent system for optimized control, primarily due to its remarkable precision in predicting the COP. This, combined with MPC's adeptness in leveraging comfort ranges, led to heightened operational efficiency within the system. COP of AMPC is 11.3% higher compared with thermostatic controller in summer day.

More research on the future of AMPC should be carried out in how easily and quickly can it be applied in the field.

NOMENCLATURE

The nomenclature should be located at the end of the text using the following format:

COP	coefficient of performance
AMPC	adaptive model predictive control
MPC	model predictive control
PID	proportional–integral–derivative
PT	photothermal
RTP	real-time price

Subscript

k	step k
min	minimum

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