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Enhancing smart building performance with waste heat recovery: Supply-side management, demand reduction, and peak shaving via advanced control systems

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ABSTRACT

With the increasing use of smart building technologies in modern infrastructures, a growing focus is on developing intelligent energy systems. This study focuses on a crucial part of this transition by investigating the application of a rule-based control method to harness the heat from wastewater to warm the ventilation lines in residential buildings. This research intends to enhance the integration of smart buildings into modern energy systems by prioritizing optimal performance and using creative control methods, mainly robust rule-based control schemes, thereby addressing current gaps and contributing to overall improvement. The proposed system's effectiveness is assessed and compared with a conventional model without the developed smart strategy from all facets. The system's performance was assessed using hourly, monthly, seasonal, and annual metrics, with a detailed sensitivity analysis conducted to evaluate the proposed control strategy's practicality. The findings reveal that the intelligent ventilation system achieves approximately 10% higher efficiency and conserves over 1.4 tonnes of CO2 emissions annually. Economically, the model demonstrates its feasibility through a marked reduction in heating costs, decreasing from 54.9 USD/MWh to 30.7 USD/MWh despite an initial investment of 29,032 USD. The results also show that the smart integration system maintains elevated supply air temperatures during colder months, enhancing thermal efficiency and reducing reliance on external heat sources. Economic analysis further identifies the energy wheel as the largest cost component, representing 50% of the total investment. Monthly variations in heat recovery from wastewater and production via the energy wheel suggest that integrating these elements through a dynamic control system leads to significant operational savings and reduces the need for local district heating. During peak demand periods, radiators serve as the primary heating source. Air-handling units provide necessary ventilation and supplemental heating, allowing for efficient energy distribution and management across all seasons.

1. Introduction

1.1. The literature survey

For the past few decades, global energy usage has consistently increased for various primary energy sources such as fossil fuels, nuclear energy, and renewable sources like solar, wind, and hydropower. Fossil fuels, including coal, oil, and natural gas, are the most commonly utilized energy sources worldwide, accounting for approximately 80 % of global energy usage [1]. Nonetheless, their utilization has led to significant environmental issues, such as air pollution and greenhouse gas (GHG) emissions, resulting in climate change [2]. As the world's population grows and developing countries increase their industrialization and urbanization, the need for energy is anticipated to continue to rise. Consequently, governments and energy companies are progressively investing in renewable energy sources like solar and wind power to lessen carbon emissions, increase cost-effectiveness [3], and mitigate the adverse effects of climate change [4]. However, switching to renewable energy and reducing our reliance on fossil fuels is gradual. In the interim, energy conservation and improved energy efficiency are essential in reducing our environmental impact [5].

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Nomenclature

Abbreviations

AHU	Air handling unit
CRF	Capital recovery factor
DH	District heating
DHW	Domestic hot water
ERV	Energy recovery ventilator
EW	Energy wheel
EAHP	Exhaust air heat pump
GHG	Greenhouse gas
HRV	Heat recovery ventilation
HVAC	Heating, ventilation, and air conditioning
HX	Heat exchanger
IAQ	Indoor air quality
KPI	Key performance factor
LCOH	Levelized cost of heating
MVHR	Mechanical ventilation with heat recovery
NZEB	Net-zero energy buildings
RBC	Rule-based control
TRNSYS	Transient system simulation tool
WW	Wastewater
WWHP	Wastewater heat pump

Latin and Greek Letters

η_{HX}	Heat recovery efficiency of heat exchanger [-]
η_{wheel}	Heat recovery efficiency of energy wheel [-]
ε_{CO_2}	Emission index [kg.MWh^{-1}]
τ	Working hours [h]
γ	Fixed cost coefficient
$C_{P_{air}}$	Specific heat of air [kJ.kg^{-1}°C^{-1}]
$\dot{m}$	Mass flow rate [kg.s^{-1}]
$\dot{Q}$	Heating demand [W]
T	Temperature [°C]
V_{tank}	Wastewater storage tank volume [m^3]
T_{low}	Wastewater lowest permissible temperature [°C]
Z	Cost [$]
$\dot{Z}$	Cost rate [$.h^{-1}]

The CO_2 emissions rate per energy unit produced is a crucial measure to assess the ecological impact of diverse energy sources like renewable energy, nuclear power, and fossil fuels such as coal, oil, and natural gas [6]. Fossil fuels have a higher CO_2 emission rate per produced energy than renewable energy sources, such as solar, wind, and hydropower, because their combustion discharges substantial amounts of carbon dioxide into the atmosphere, exacerbating climate change and other environmental problems [7]. In order to mitigate the impact of climate change and achieve a sustainable energy future, it is essential to reduce the CO_2 emission rate per unit of energy produced, which can be accomplished by transitioning to cleaner and sustainable energy sources, as well as enhancing energy efficiency in various sectors such as transportation, industry, and buildings [8]. Governments, businesses, and individuals can also play their part in reducing their carbon footprint by adopting demand-side energy management, promoting renewable energy use, and reducing energy usage through behavioral changes [9]. Reducing the CO_2 emission rate per unit of energy produced will help preserve the environment, ensure energy security, and create a sustainable future for all.

China is investing heavily in renewable energy sources such as wind and solar power to decrease its reliance on coal and lower its CO_2 emissions per unit of energy produced [10]. The International Energy Agency reports that in 2020, China set a record by adding 136 GW of renewable energy capacity, accounting for 72 % of the global growth in renewable energy [11]. However, the issue of CO_2 emissions per unit of energy produced in China is multifaceted and evolving. It is influenced by various factors such as economic growth, energy demand, and government policies. The CO_2 emission rate varies depending on the type of energy source utilized. In 2021, China's energy-related CO_2 emissions were the highest worldwide, totaling 11.9 gigatons [12]. The average CO_2 emission rate for electricity generation in China was around 772 g of CO_2 per kWh in 2019 [13]. Coal, which is the primary energy source in China, has a higher CO_2 emission rate per unit of energy produced than other energy sources and emitted approximately 10.05 billion metric tons of CO_2 in 2019, according to the Global Energy Monitor [14]. Coal-fired power plants in China emit an average of roughly 1050 g of CO_2 per kWh. In contrast, renewable energy sources such as solar and wind power have almost zero CO_2 emissions during their operation. As a result, China is significantly investing in renewable energy sources to reduce its dependence on coal and lower its CO_2 emissions per unit of energy produced [15,16].

Given the pressing global challenge of rising energy consumption and the corresponding increase in carbon emissions, particularly evident in rapidly industrializing nations like China, there is an urgent need for sustainable solutions [17]. China, being one of the largest contributors to global emissions, faces the dual challenge of continuing its development while mitigating environmental impacts. This necessitates innovative approaches that not only reduce energy consumption but also harness cleaner energy sources. One such promising approach is the development of near-zero energy buildings in stable distribution systems, which aim to significantly lower energy demand and incorporate advanced energy recovery techniques [18]. These buildings leverage renewable energy sources, thus presenting a viable pathway to achieving substantial reductions in carbon emissions while supporting China's urbanization and growth [19,20].

The objective of achieving net-zero energy buildings is in line with a considerable decrease in energy usage and necessitates the utilization of renewable energy sources [21]. Enhancing building heat recovery is a highly effective strategy to attain this target [22,23]. The process involves capturing waste heat from diverse sources within the building, including exhaust air, hot water, or industrial operations, and reusing it for space heating or hot water [24]. This method leads to a sustainable and energy-efficient building, significantly reducing the energy required for heating and cooling. Additionally, enhancing building heat recovery results in economic benefits, such as lower energy bills and decreased maintenance costs. It also improves indoor air quality (IAQ) and occupant comfort by providing consistent and pleasant temperatures throughout the building [25]. Implementing heat recovery systems in buildings contributes to global climate goals by decreasing greenhouse gas emissions associated with energy consumption. Overall, enhancing heat recovery in buildings is a practical and cost-effective approach towards reaching net-zero energy buildings [26], providing benefits to the environment, the economy, and building inhabitants [27].

While energy recovery in buildings may not be identical to utilizing renewable resources, it can be equally effective in reducing wasted energy and improving energy efficiency. Energy recovery entails capturing and reusing energy that would typically be lost during heating, ventilation, and air conditioning (HVAC) operations, accomplished through heat recovery ventilators (HRVs) or energy recovery ventilators (ERVs) [28]. Conversely, renewable resources are naturally replenished energy sources, such as solar, wind, hydro, and geothermal. Unlike energy recovery in buildings, renewable resources increase the overall energy supply and can offer long-term sustainable solutions for energy needs [29]. Despite differences in the energy sources they provide, both energy recovery in buildings and renewable resources are critical for reducing energy waste and boosting energy efficiency. Combining these approaches can help establish a more sustainable and responsible energy future for generations to come.

Wastewater heat recovery is becoming increasingly crucial in buildings to lower energy usage and expenses [30,31]. This process involves retrieving and reusing heat generated from activities like showering, bathing, and washing, which can be redirected for space and water heating to decrease the need for additional energy sources [32,33]. By recuperating heat that would otherwise be lost, buildings can realize considerable energy savings, diminish their carbon footprint, and enhance their sustainability. Furthermore, since wastewater is a reliable thermal energy source, wastewater heat recovery systems can offer a steady and dependable heat source, making them especially valuable in colder climates with high energy requirements. Additionally, wastewater heat recovery systems generate substantial cost savings over time, notwithstanding their high initial installation costs [34]. These systems can also lengthen the lifespan of a building's heating equipment by reducing the system's workload and offering cost savings and other benefits to building occupants and owners.

Supply air temperature is a critical factor affecting both buildings' heating demand and indoor air quality. The HVAC system delivers the supply air temperature to the occupied areas of the building. If the supply air temperature is too low, the indoor space will feel cold, and occupants will need more heating, resulting in higher heating demand. In addition, freezing is a common problem in cold climate regions due to cold outdoor air entering the ventilation heat recovery exchangers [25]. In contrast, if the supply air temperature is too high, the building may become too warm, causing excessive cooling demand and increased energy usage. Moreover, the supply air temperature significantly impacts the indoor air quality of buildings. A low supply air temperature can lead to condensation and moisture accumulation in the building's envelope and indoor surfaces, promoting mold growth and other indoor pollutants [35]. Conversely, high supply air temperatures can cause dry indoor air, leading to respiratory problems and discomfort for building occupants. Therefore, maintaining an optimal supply air temperature range is crucial to ensure occupant comfort and good indoor air quality while reducing heating demand and energy usage [36].

The cost-effectiveness of building energy systems shows a noticeable improvement as wastewater potential increases to a certain threshold. Several corroborative studies support this finding. For instance, Bertrand et al. [37] proposed methodologies to quantify building-specific energy costs and the potential for energy savings based on in-building wastewater heat recovery systems. Their research indicated that such systems can achieve integrated energy savings of 28 %-41 % in high-efficiency buildings. Golzar and Silviera [38] investigated the influence of wastewater heat recovery on centralized energy recovery performance. They demonstrated that heat loss in the sewage system can lead to 5 % − 9 % lower heat recovery in centralized district heating systems compared to in-building heat recovery. Additionally, Xu et al. [39] reviewed various heat recovery technologies for building applications. They suggested that combining heat recovery with energy-efficient systems is a promising approach to reducing greenhouse gas emissions, thereby enabling residential buildings to meet high performance and comfort standards. By incorporating these corroborative studies, we aim to provide a comprehensive understanding of the principles underpinning our observations. These references validate the relationship between ventilation heat recovery efficiency, levelized heating costs, and the significant role of wastewater temperature in enhancing system cost-effectiveness. The inclusion of this data underscores the potential of wastewater heat recovery systems to contribute meaningfully to sustainable building practices, ultimately supporting global climate goals.

1.2. The scientific contribution

Therefore, the primary objective of this article is to explore a new approach to minimize the total energy loss in multi-residential buildings by recovering waste heat from exhaust air and wastewater. Specifically, we aim to harness the extra heat from wastewater and utilize it to augment the supply air temperature to the building, thereby reducing the overall heating demand of the building. Our approach takes into account the economic and environmental effects of applying this solution, and we will conduct a comprehensive analysis to determine the long-term feasibility of this approach. By assessing the installed components and considering their impact on reducing the building's energy demand, an optimized, sustainable solution that supports both environmental and economic benefits can be achieved [40].

The innovation of our research lies in the simultaneous integration of wastewater heat recovery and exhaust air heat recovery within a single system. Prior studies have either focused on individual waste energy recovery systems or implemented both systems in buildings but operated them independently. Our approach, however, synergistically combines these two systems to enhance overall efficiency. This integration increases the supply air temperature, thereby reducing ventilation heat losses. Moreover, our system eliminates the need for energy-intensive devices like exhaust air heat pumps (EAHP) or wastewater heat pumps (WWHP), significantly improving economic feasibility for existing and new building installations. Additionally, we employ a rule-based control (RBC) strategy, which optimizes the operation of the integrated system by ensuring maximum efficiency and adaptability to varying building demands [41]. This innovative approach not only optimizes energy recovery but also offers a practical, cost-effective solution for micro-grid decentralized energy systems in sustainable building design [42].

2. The smart building energy system

This study aims to enhance the effectiveness of the ventilation system of a multi-residential building located in the climatic zone of Beijing. To achieve this, the researchers conducted transient simulations using the TRNSYS [43] software to evaluate the performance of the heat recovery systems installed in the building. The evaluation focused on several key factors, including the heating demand, ventilation temperatures, and the economic and environmental impacts of the proposed heat recovery systems. The findings of this study will provide valuable insights into the optimal design and operation of ventilation systems in similar buildings in the region, thereby promoting energy efficiency and reducing greenhouse gas emissions.

2.1. The studied system

In Fig. 1, a schematic representation of the investigated system is observed. The suggested heat recovery add-ins aimed at optimizing energy usage and reducing heat waste from major sources such as buildings, ventilated air, and wastewater are illustrated in this configuration. This innovative setup fully tackles the challenge of waste heat. Firstly, a district heating (DH) substation provides a space heating source. Secondly, the released wastewater enters a heat recovery loop after being roughly purified. Urban residential areas typically generate 120–180 L of discarded wastewater per person [44], with temperature and flow rates varying based on daily timing and occupant density [45,46]. The warm wastewater feeds into the air preheater, which helps raise the incoming air temperature. Wastewater can be cooled to various temperatures depending on the outdoor air temperature and its flow rate to AHU. The cooled wastewater returns to the bottom of the storage tank (to maintain the temperature stratification) or is discarded to the sewerage. This depends on the wastewater outflow from the building. When the outdoor temperatures are near the desired temperature for the air supply, the air preheater cycle ceases to function. The heat recovery ventilation system provides treated fresh air to the building and effectively recovers the energy used in the process. The temperature of the supply air has a direct impact on both the heating requirement of the building and the level of indoor thermal comfort perceived by the inhabitants. When the external temperatures are low, the heat that is

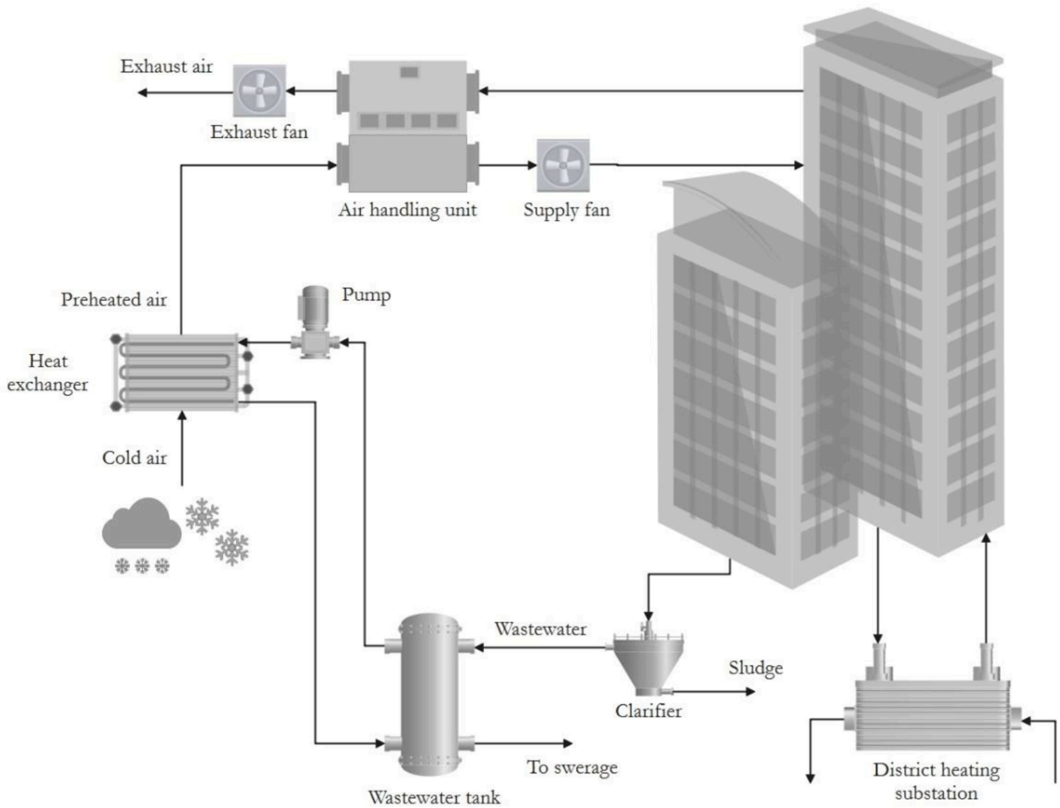

Fig. 1. Schematic illustration of the heat recovery systems and improved ventilation.

obtained from the wastewater is utilized to raise the temperature of the incoming air. This, in turn, increases the temperature of the air supplied to the building, leading to enhanced indoor thermal comfort and decreased need for heating the building. The proposed system provides a sustainable and effective solution to reduce waste heat and optimize energy usage in buildings.

The rule-based control approach is the fundamental element of the intelligent ventilation system, which is responsible for its exceptional energy efficiency and thermal management performance. This approach entails a predetermined set of regulations that dictate the functioning of the crucial elements of the system, such as the energy wheel and the wastewater heat exchanger. The rule-based controller optimizes the use of thermal energy by altering parameters such as flow rates, temperature setpoints, and operational modes depending on real-time environmental data and building conditions. This clever adaptation optimizes heat extraction from wastewater and exhaust air while decreasing the need for external heating sources. The controller focuses on maintaining elevated supply air temperatures throughout colder months, hence improving thermal comfort and decreasing heating demand. The rule-based control technique effectively balances energy input and output

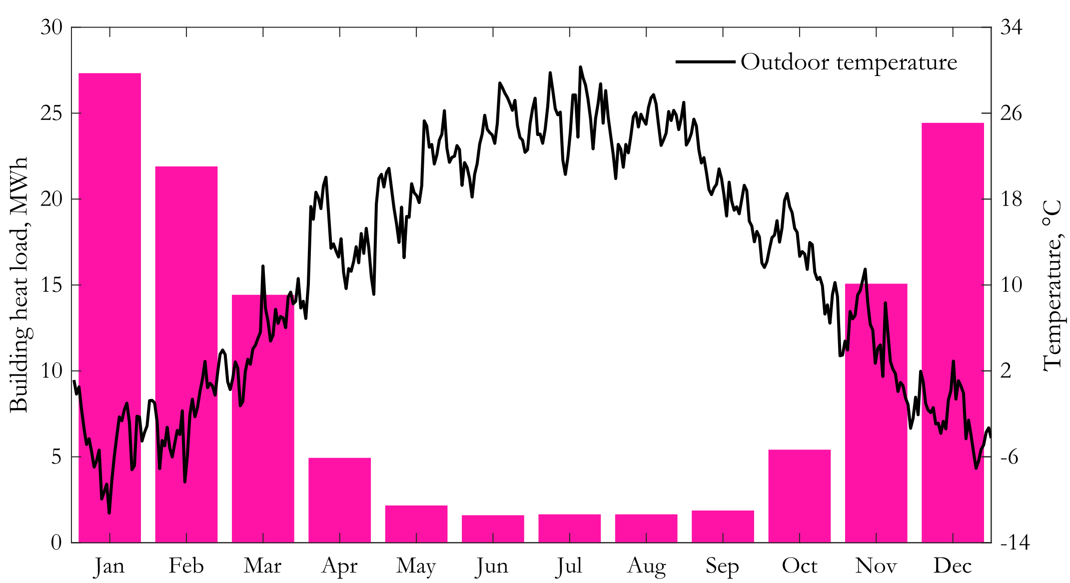

Fig. 2. Building heating demand without heat recovery installations and outdoor temperature in Beijing.

by continually monitoring and responding to variations in external temperature, indoor heating demand, and wastewater temperature. This ensures consistent performance and leads to significant cost savings throughout the year. This method increases energy efficiency and significantly decreases CO_2 emissions, showcasing the environmental and economic feasibility of the intelligent ventilation system.

2.2. The building case

The building under study is a six-story residential apartment located in Beijing. The building has a total living area of 2050 m^2, including 23 apartments, first used in 2007. It is equipped with a mechanical ventilation system with heat recovery (MVHR). The study focuses on the building's heating requirements, and Fig. 2 provides a detailed breakdown of the monthly heating demand for the building without any heat recovery systems. The graph also shows the outdoor temperature in Beijing throughout the year. The city experiences a wide range of temperatures, with the lowest recorded daily temperature of −11.2 °C and the lowest hourly temperature of −15 °C. In contrast, the highest recorded daily temperature is 30.3 °C, with the highest hourly temperature being 37.4 °C. This temperature variation highlights the challenges of maintaining a comfortable living environment within the building and the need for an effective heating and cooling system.

Ensuring an optimal indoor environment and sufficient supply of fresh air to indoors accentuates the significance of the ventilation system in establishing a heat equilibrium within the building. Enhancing the efficiency of the ventilation performance can substantially reduce notable heat losses experienced during the coldest months, as depicted in Fig. 2. The subsequent sections illustrate how harnessing wastewater heat can profoundly impact ventilation losses in the most effective manner.

3. Method

3.1. Transient system simulation software

To evaluate the system's performance before and after optimization changes and highlight the impact of air preheating in cold winter conditions, we run yearly dynamic simulations using TRNSYS software. These simulations evaluate the energy demand of the building under study and compare supply temperatures after modifications, showcasing the advantages of heat recovery methods. Table 1 presents an overview of key simulation components in TRNSYS used for simulating and optimizing system performance:

In the present work, TRNSYS software is predominantly utilized as an equation-solving tool based on common numerical methodologies for validating the components. TRNSYS models each physical piece of thermodynamic equipment using a component that has been created using Fortran source code. A multitude of persons have authored TRNSYS components, verified their accuracy using experimental data, and granted the University of Wisconsin Madison Solar Lab authorization to distribute these components to other TRNSYS users. The source code and description of these components have been uploaded online. Furthermore, the TRNSYS handbook includes a comprehensive compilation of references for each standard component. Thus, as a result, there is no longer a requirement to validate TRNSYS component models. In the literature, several articles have simulated HVAC systems using TRNSYS but have not validated the components [50–59].

3.2. Performance indicators

The performance of the studied system is assessed by examining total energy savings and associated costs. Although the additional components required to capture and utilize recovered wastewater energy contribute to upfront investment costs, these costs may be offset by the energy savings achieved and the associated reduction in environmental impact. To thoroughly evaluate this balance, a parametric study is conducted, analyzing various design parameters of system components to determine their impact on overall energy savings and CO_2 emission reduction. This approach allows for a comprehensive understanding of the trade-offs between initial investment and long-term sustainability benefits, ultimately guiding the development of cost-effective and environmentally favorable design solutions. These parameters are the heat recovery efficiencies at the AHU and the wastewater heat exchanger, the storage tank volume, the total living area occupied by a person in the building, and the lowest temperature at which wastewater can be cooled. These parameters identify the system performance, showing the total energy savings per cost and the total CO_2 emission.

The techno-economic-environmental investigation deals with finding the entire system's performance efficiency, levelized cost of heating (LCOH), total investment cost, and CO_2 saving. Therefore, the performance efficiency of the system is defined by equation (1):

$$\eta = \frac{T_{supply,zone} - T_{Outdoor}}{T_{return,zone} - T_{Outdoor}} \times 100 \tag{1}$$

where, $T_{supply,zone}$, $T_{return,zone}$, and $T_{Outdoor}$ are the supply and return air temperatures to/from the building and the outdoor temperature, respectively. The economic evaluation uses the particular cost theory to determine the total cost rate, as denoted by Equation (2) [60,61].

$$\dot{Z}_{Total} = \dot{Z}_{Investment} + \dot{Z}_{Operating\&Maintenance} \tag{2}$$

$$Z_{Investment} = Z_{WWTank} + Z_{AHU} + Z_{Pump} + Z_{Fan} + Z_{AirPrehater} + Z_{Controllers} \tag{3}$$

$$\dot{Z}_{Captialinvestment} = \left(\frac{CRF}{\tau}\right) \times Z_{Investment} \tag{4}$$

Table 1
System components and the corresponding TRNSYS Types used in simulations [47–49].

System component	TRNSYS component	Type No.	Details
Rotary heat exchanger	Energy wheel	667d	Simulates temperature and moisture exchange between exhaust and supply air streams. Psychrometric routines assess air properties.
WW heat exchanger	Heat exchanger Keep hot side above a minimum	699	Models water-to-air heat transfer from wastewater to outdoor air for the HRV. The bypass criterion ensures adequate minimum wastewater temperature for cold air.
Supply/ exhaust fan	Fan – Input the flowrate	744	Takes in air properties and uses the psychrometrics routines to return the temperature, humidity ratio, relative humidity, and enthalpy values.
WW tank	Cylindrical storage tank – No HX	534	Utilizes a temperature-stratified tank for building wastewater. Ten vertical nodes maintain temperature stratification, with warm wastewater supplied from the top and cold return/discard connected to the bottom.
Building	Simple Building Multi-zone capability with internal controls	660	Models a multi-zone building with internal controls for setting indoor temperatures and calculating heating demands. It accounts for ventilation, outdoor infiltration, heat losses, and internal gains at each timestep.

$$\dot{Z}_{Operating\&Maintenance} = \left(\frac{\gamma}{\tau}\right) \times Z_{Investment} \tag{5}$$

The LCOH is determined by dividing the total cost rate by heating production, serving as a metric to assess the cost-effectiveness of the proposed smart system in dollars per megawatt. The total cost rate ($\dot{Z}_{Total}$) is expressed as the combination of the investment costs and the operating and maintenance costs. Additionally, *CRF*, τ, and γ represent the capital recovery factor, working hours, and fixed cost coefficient, respectively [62]:

$$LCOH = \frac{\dot{Z}_{Total}}{\dot{Q}_{Total}} \tag{6}$$

$$\dot{Q}_{Total} = \dot{m}_{Air} \times C_{P,Air} \times (T_{in,zone} - T_{Outdoor}) \tag{7}$$

Similarly, $\dot{Q}_{Total}$ represents the total heating transferred to the building and the evaluation of CO_2 saving is conducted to measure the proposed system's environmental advantages compared to a comparable system lacking a wastewater heat recovery unit [7].

$$CO_2saving = \left(\dot{Q}_{Total,withoutWW} - \dot{Q}_{Total,withWW}\right) \times \varepsilon_{CO2} \tag{8}$$

The heat transferred to the building in the proposed smart building with wastewater heat recovery, denoted as $\dot{Q}_{Total,withWW}$, contrasts with the heat output of the conventional model lacking such recovery, represented as $\dot{Q}_{Total,withoutww}$. Additionally, ε_{CO2}, equivalent to 550 kg/MWh, symbolizes the emission index of the conventional system in China [13].

4. Results and Discussions

After simulating the proposed smart model in TRNSYS, a comprehensive technical, environmental, and economic evaluation is conducted and compared with the conventional system without the wastewater heat recovery strategy. For this, the key metrics, including the performance efficiency, investment costs, heating costs, and heating generated by the air handling unit and supplied by the radiators, are assessed through the year, season, month, and hour. Additionally, sensitivity assessment is carried out to analyze how the efficiency, investment costs, and heating costs are affected when the significant variables, including the energy wheel's epsilon, wastewater temperature leaving the tank, number of residences, and heat exchanger's epsilon, are changed.

Table 2 compares the efficiency, investment, and heating costs of the proposed smart model equipped with the wastewater heat recovery strategy with the conventional system. According to the table, the effectiveness of the conventional ventilation system is 85 %. This indicates that while 15 % of the energy input is wasted as waste heat, the remaining 85 % is successfully used for heating. However, when combined with a wastewater heat recovery technique, the suggested intelligent ventilation system increases efficiency to 95.4 %. The huge rise in numbers demonstrates the successful implementation of the heat recovery system, which effectively absorbs and utilizes thermal energy from wastewater. This results in reduced energy wastage and a notable enhancement in the system's overall energy efficiency. The table further indicates that the smart model necessitates a more significant initial cost of 29,032 USD when implementing the wastewater heat recovery approach. The increase is due to the additional components and technology required to capture and reuse heat from wastewater. Although the initial cost is higher, the investment in the heat recovery system can be rationalized due to its long-term savings and increased efficiency. This is justified due to the substantial decrease in heating costs (from 54.9 USD to 30.7 USD per MWh), as indicated in Table 2. To establish a more easily understandable measure of the investment cost, we have standardized the total investment by considering a total area of 2050 m^2, which includes 23 flats with four occupants in each apartment. As indicated in the table, the normalized investment costs for the conventional system are 5.9 USD/m^2 and 132 USD/person whle the corresponding values for the porposed novel system with wasteheat recovery are 14.2 USD/m^2 and 315.5 USD/person. Finally, it can be observed that the proposed smart integration results in 1.47 tonnes/year of CO_2 saving compared to a similar system without wastewater heat recovery.

Table 2
The comparison of main metrics with and without wastewater heat recovery strategy.

System Strategy System metric	without wastewater heat recovery	with wastewater heat recovery
Efficiency (%)	85 (nominal)	95.4
Investment cost (USD)	12,142	29,032
Heat cost (USD/MWh)	54.9	30.7
Normalized investment cost per floor area (USD/m^2)	5.9	14.2
Normalized investment cost per person (USD/person)	132	315.5
CO_2 saving (Tonnes)	–	1.47

Fig. 3 compares the hourly variation of supply air temperature entering the room from the ventilation system and the time duration curve of space heating demand with and without wastewater heat recovery strategy to look into the effectiveness of the proposed smart integration in detail. According to Fig. 3(a), during the cold hours when the building requires heat, the air supply temperature of the proposed model equipped with wastewater heat recovery has higher values, leading to improved thermal efficiency and reduced primary energy used. Fig. 3(b) demonstrates a consistent reduction of space heating demand across various time points, indicating the reduction of reliance on any external heat source. Significant energy savings are shown by the reduced need for space heating while employing the wastewater heat recovery system. The technology lowers energy use and operating costs by reducing the need for extra heating through heat recovery from wastewater. The benefits of incorporating a wastewater heat recovery method into the smart ventilation system are clearly demonstrated by evaluating the supply air temperature and space heating demand trends. Thanks to better energy efficiency, more thermal comfort, and substantial long-term savings, the higher supply air temperatures and lower heating demands make the extra expenditure worthwhile. This decrease in primary energy use highlights the system's capacity to maximize energy efficiency while preserving pleasant indoor temperatures.

Thermal energy storage (TES) systems incorporating stratification have notable advantages in maximizing energy efficiency and improving system performance. Stratification is the process of water naturally separating into separate layers based on temperature within the storage tank, with hotter water at the top and cooler water at the bottom. Temperature layering enables the system to extract the necessary water temperature from the relevant layer, reducing the need for extra heating or cooling and optimizing the utilization of stored thermal energy. Stratified TES systems can enhance energy utilization, save operational expenses, and prolong the lifespan of HVAC equipment. In order to reflect the effect of stratification over the tank, Fig. 5 illustrates the hourly variation of the temperature at the 1st and 10th nodes and the average tank temperature. Fig. 4 shows the schematic of the storage tank, inflows and outflows, and the stratification nodes used in the simulation.

The temperature at Node 1 remains consistently elevated and stable for most of the period, with an initial average of approximately 20 °C and subsequent minor fluctuations. This suggests that the uppermost layer of the tank, where hot water is held, can maintain higher temperatures with great efficiency. Node 10′s temperature shows large variations, from 14.7 °C to 18.9 °C. The temperature changes observed in the tank's bottom layer, which contains cooler water, appear more dynamic due to the heat being added and removed from the tank. The average temperature exhibits a pattern that falls within the temperature

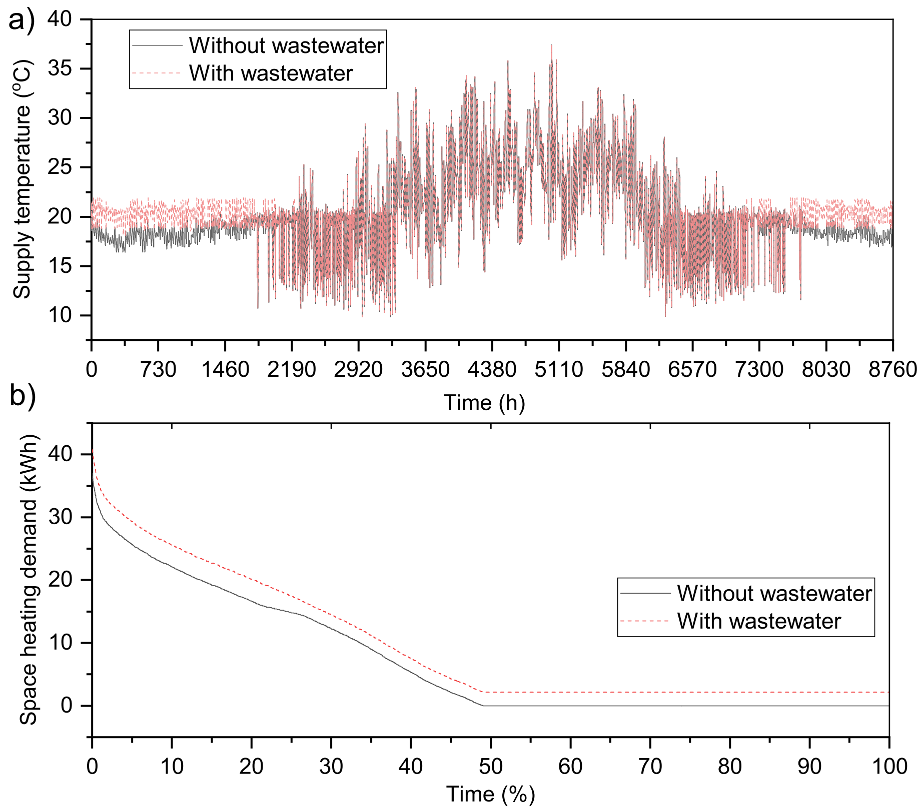

Fig. 3. The comparison of a) hourly changes in supply air temperature entering the room and b) time duration curve of space heating demand with and without wastewater heat recovery strategy.

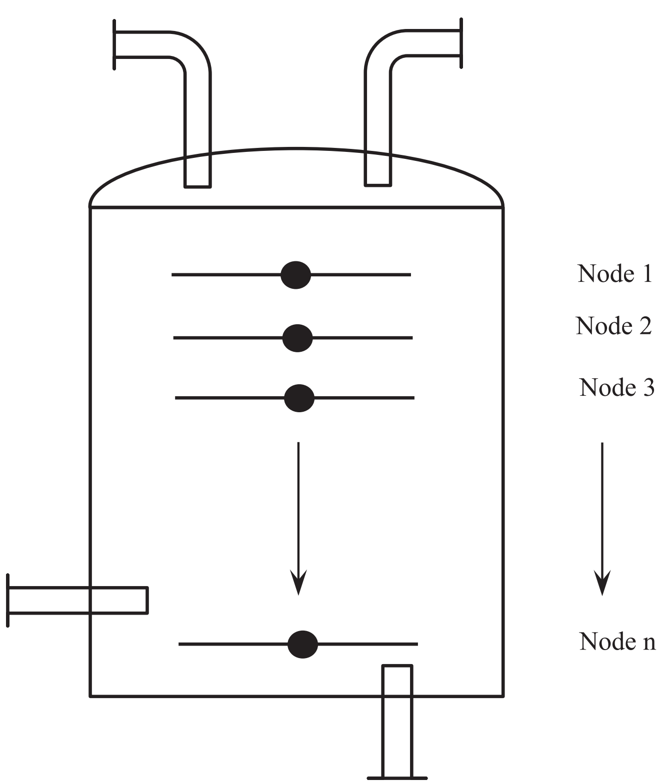

Fig. 4. The schematic of the thermal energy storage tank.

range of Node 1 and Node 10. The temperature initially begins at approximately 20 °C, lowers during intensified heat extraction, and gradually rises when heat is reintroduced into the tank.

Fig. 6 shows the investment cost of each component and its proportion in the overall costs. The energy wheel is the system's most costly component, accounting for around 50 % of the total investment cost. Its effectiveness in lowering total energy use and enhancing the system's thermal performance justifies its high cost. The tank is the second most expensive component, with an initial cost of 4,000 USD. Because robust substances that can resist thermal expansion and contraction and effectively insulate against heat loss are required, the cost is somewhat expensive. Also, it can be observed that the heat exchanger, with almost a 12 % share of the total investment cost, is a key component from the economic point of view. The figure further illustrates that the cheaper elements, like the fan, valves, and pump, are easily accessible in typical designs and perform necessary but simpler tasks.

Fig. 7 compares the monthly share of heat generated from the wastewater and recovered via the energy wheel to analyze the impact of each source on improving the air supply temperature. The energy wheel exhibits substantial heat recovery from January to March and October to December. Between May and September, both the energy wheel and wastewater heat recovery systems exhibit minimal or no heat production, indicating reduced heating requirements during the warmer months. The energy wheel frequently outperforms the wastewater system in terms of heat recovery, demonstrating its high efficiency and efficacy in absorbing and reusing heat inside the ventilation system. The figure further reveals that although the wastewater system makes large contributions during peak months, its performance is less effective during transitional and warm months, indicating a higher sensitivity to seasonal fluctuations. This suggests that the effectiveness of wastewater heat recovery is contingent upon the presence of wastewater heat, which may vary in accordance with usage trends. The energy wheel and the wastewater heat recovery systems both show high heat recovery rates in

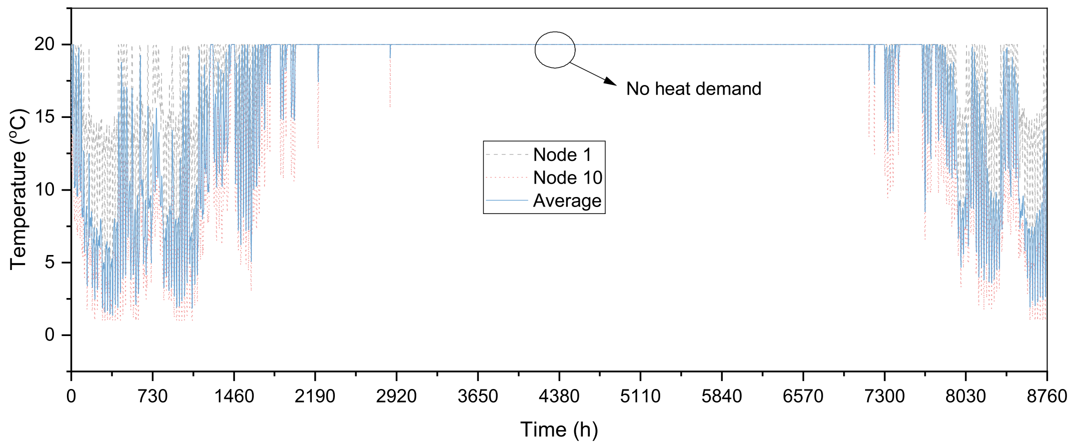

Fig. 5. The hourly changes in temperature at the first and tenth nodes and the average temperature of the stratified tank over the year.

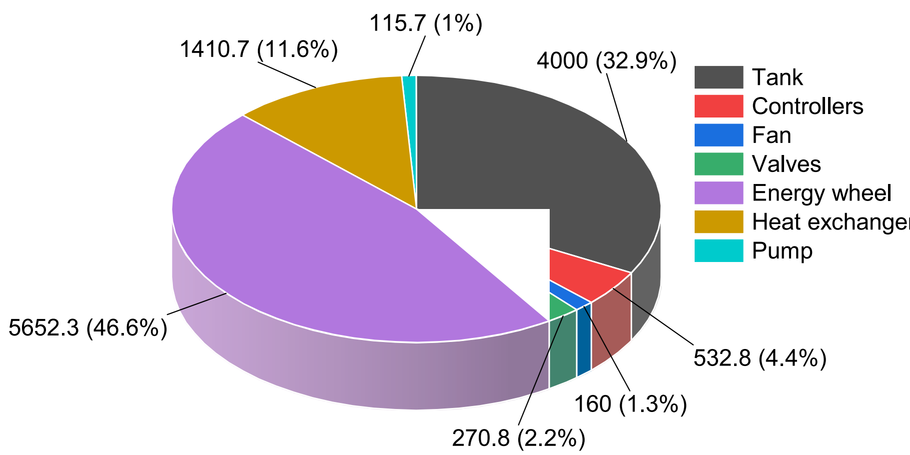

Fig. 6. The investment cost of each component in USD.

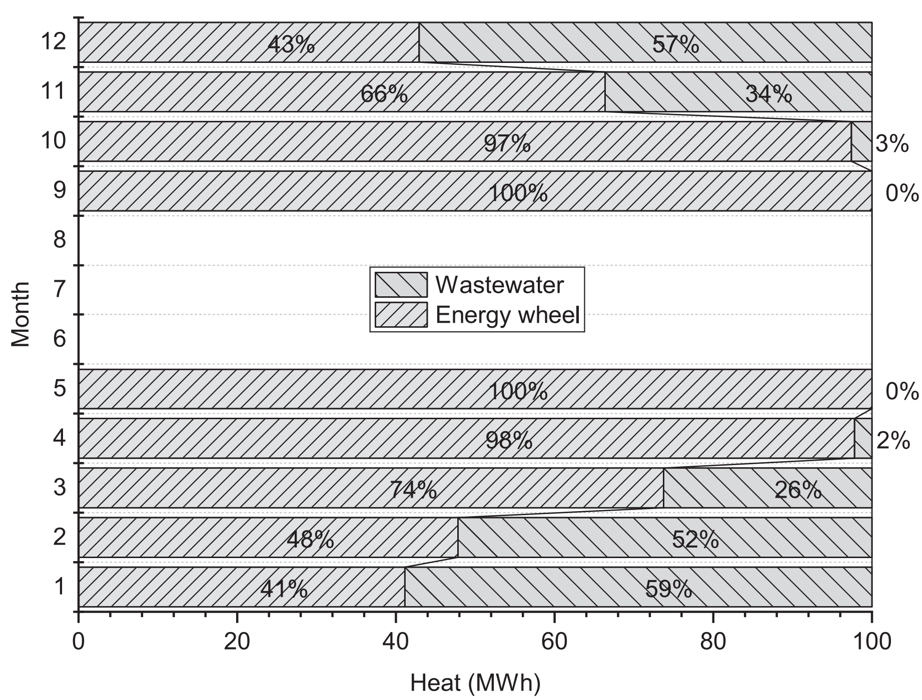

Fig. 7. The comparison of the monthly share of heat generated from the wastewater and recovered via the energy wheel.

the winter and low production in the summer. This seasonal performance means that the system is very effective when heating is at its highest and uses less energy when it's warmer outside.

In order to analyze the share of each source and compare their production in total heating demand, the heat production by the air handling unit and the radiators is illustrated in Fig. 8. Radiators emit substantially greater heat than air-handling units all around the year. In January, radiators generate 16.4 MWh of energy, whereas the AHU generates 8.9 MWh. This pattern remains constant throughout the colder months, indicating that radiators are crucial in supplying primary heating during high demand. The AHU provides additional heating, guarantees sufficient ventilation, and preserves indoor air quality. The reduced contribution of this device, in comparison to radiators, indicates that its primary function is to assist in temperature regulation rather than serving as the major source of warmth. The decrease in heating contributions during the warmer months (May to September) results from effective energy management, which prevents wasteful heating when the ambient temperatures are elevated. The figure shows that combining air AHU and radiators achieves a balanced and effective heating system. During periods of high demand, radiators play a more prominent role, while the AHU assists by ensuring proper ventilation and providing extra heat as necessary.

Fig. 9 compares the monthly and seasonal variation of heat provided by the air handling unit via wastewater heat recovery and/or energy wheels. The AHU generates the highest amount of heat from December to February, reaching its maximum levels in January (8.9 MWh) and December (8.2 MWh). This increased demand is due to the lower temperatures outside, necessitating substantial heating to keep the indoor environment comfortable. The heat output of the AHU decreases significantly throughout the summer months, reaching values that are either at or very close to 0 MWh. This suggests a low need for heating due to higher ambient temperatures. The seasonal changes show that the maximum productions of 22.2 MWh and 15.9 MWh correspond to Winter and Autumn because the high heating demands require more input energy to maintain the indoor environment within the comfort zone. The seasonal differences in heat production demonstrate how well the system adjusts to shifting weather patterns and makes sure energy isn't squandered when it's not needed.

Sensitivity analysis is an essential tool for assessing parameters in smart energy systems, providing multiple advantages. Sensitivity analysis is a method that involves systematically changing input parameters to determine which variables have the most influence on the

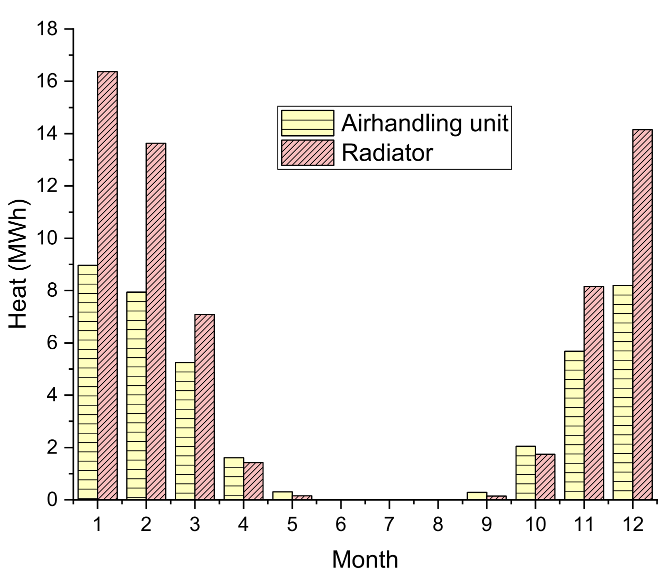

Fig. 8. The comparison of the monthly share of heat provided by the air handling unit and radiators.

performance and efficiency of energy systems. This method improves the comprehension of system behavior, resulting in more resilient and dependable models. It assists in prioritizing research and allocating resources by emphasizing the crucial elements that impact energy optimization and sustainability, therefore enhancing decision-making processes. Fig. 10 demonstrates the variation of main metrics, including efficiency, investment cost, and heating price, with key variables like the energy wheel's epsilon, wastewater temperature leaving the tank, number of residences, and heat exchanger's epsilon. According to Fig. 10(a), as the epsilon value of the energy wheel goes from 0.7 to 0.9, there is a corresponding improvement in the system's efficiency. The upward trajectory suggests that increasing epsilon values improves energy wheel performance, raising the system's overall efficiency. The reason for this is probably the enhanced heat transfer capabilities, which lead to a more efficient preheating of the air inlet.

With the increase in epsilon, the investment cost likewise exhibits a rising trend. The price progressively increases to 14,200 USD at an epsilon of 0.9 from 12,500 USD at an epsilon of 0.7. The greater capital cost necessary for more sophisticated energy wheels with improved performance attributes is reflected in this trend. Similar growing trends are seen in the levelized cost of heating, albeit comparatively small compared to investment and efficiency costs. An epsilon of 0.7 begins at 30.7 USD per MWh and rises to 32.3 USD per MWh with an epsilon of 0.9. This rise can be ascribed to the greater maintenance costs related to better-efficiency systems and potential investment costs. In summary, raising the energy wheel's epsilon increases efficiency but also raises investment and heating costs. These patterns emphasize how crucial it is to balance cost-benefit analysis with performance enhancements while developing and refining these systems.

Fig. 10(b) demonstrates the system's efficiency is relatively stable for most of the wastewater temperature range exiting the tank, averaging 94.7 %. This implies that the system's efficiency is reasonably steady within the given temperature range, suggesting that variables other than wastewater temperature may significantly impact efficiency. The investment cost remains at 13,700 USD for most of the temperature range. There is a gradual decline in temperature starting at 4.55 °C, reaching a value of 13,500 USD at 6.3 °C, followed by an increase to 14,000 USD at 7 °C. This trend indicates that the system's cost-effectiveness improves marginally as the wastewater temperature exiting the tank increases to a certain threshold. However, greater temperatures may need more sophisticated or supplementary components beyond this point, leading to increased investment costs. The figure further shows that the heating cost remains quite stable, with few fluctuations, at approximately 31.9 USD per MWh for temperatures up to 4.9 °C. There is a small decline, dropping to 31.3 USD per MWh at 6.3 °C and then rising to 32.6 USD per MWh at 7 °C. This pattern is consistent with the relationship between heating prices and investment costs. As heating prices decrease, there is a minor decrease in investment costs up to a certain point. However, as temperatures rise beyond that point, the costs of investment increase. Based on the trends observed, it can be concluded that the system's efficiency remains consistent with a moderate range of wastewater temperatures that leave the tank. However, both investment costs and heating prices exhibit slight enhancements before rising again at higher temperatures.

Fig. 10(c) depicts that the system's efficiency increases as the number of occupies rises. It increases gradually to 95.8 % efficiency with 80 dwellings from 92.8 % efficiency with 40 residences. This pattern indicates that as the system handles higher loads, its efficiency increases with the number of homes. This is probably because of economies of scale and better use of the heat recovery process. As the number of dwellings rises, the investment cost falls. For 40 residences, it starts at 16,000 USD and decreases to 12,300 USD for 80 residences. This drop in the system's per-residence cost can be explained by the fixed costs being spread over more units. Larger systems might also profit from bulk purchasing and more effective labor and material utilization. A growing number of residences leads to a drop in the heating costs. The price starts

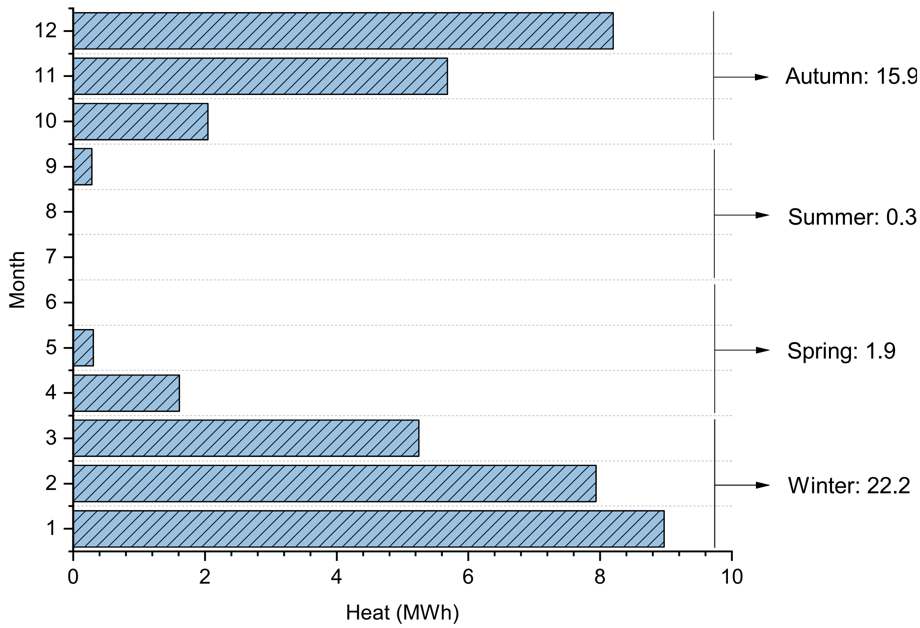

Fig. 9. The monthly changes in heat provided by the air handling unit per month per season.

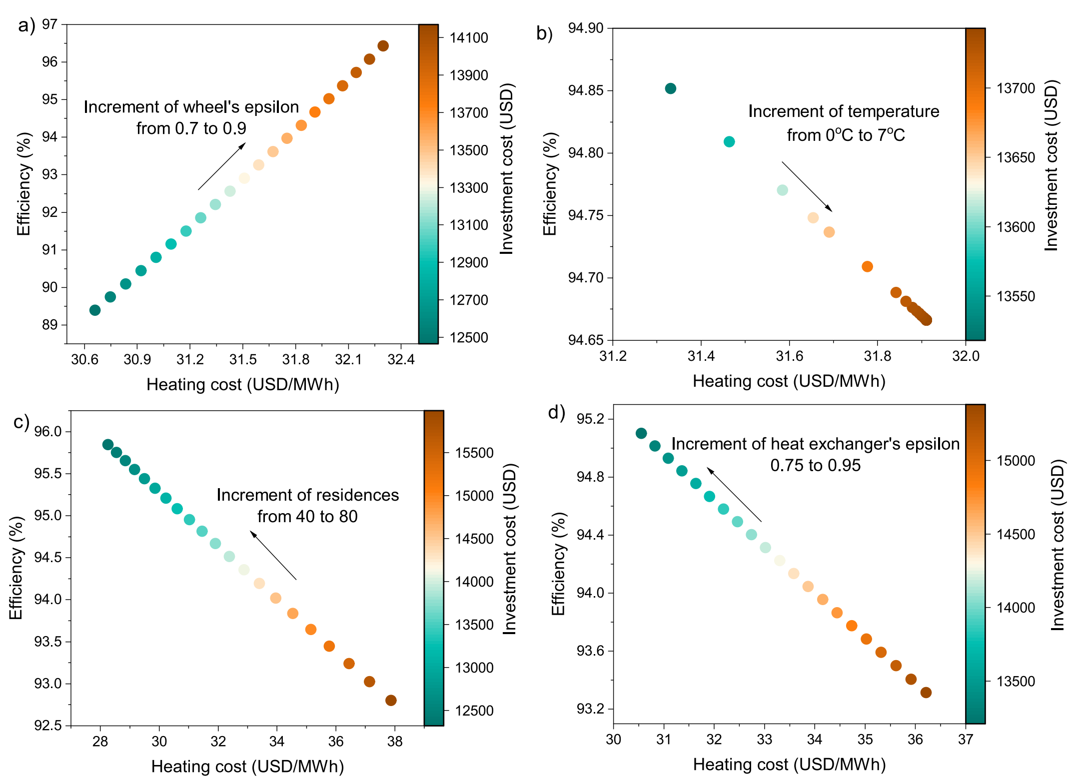

Fig. 10. The sensitivity analysis: a) energy wheel's epsilon, b) wastewater temperature exiting the tank, c) number of residences, and d) heat exchanger's epsilon.

at 37.9 USD per MWh for 40 houses and decreases to 28.3 USD per MWh for 80 residences. This decrease corresponds to the declining investment expense and demonstrates enhanced cost-effectiveness as the system caters to more households. Distributing operational costs across more units results in a reduced heating price per home.

Eventually, Fig. 10(d) shows that the system's efficiency positively correlates with enhancing the heat exchanger's efficiency. As the level of effectiveness rises, the system's efficiency likewise enhances. This is because the heat from the wastewater is transferred more efficiently to the incoming air, resulting in a more effective preheating. This decreases the energy other sources need to reach the desired indoor temperature. In most cases, the investment cost decreases as the heat exchanger becomes more efficient. Increased heat exchange efficiency lessens the load on the system, reducing the need for costly auxiliary equipment. A lower levelized cost of heating is another benefit of a more efficient heat exchanger. This reflects the lower operational expenses linked to systems with better efficiency. The total cost per unit of heat delivered decreases due to improved heat recovery, which decreases the demand for additional heating energy. Investing in more effective heat exchangers is economically beneficial, as the figure shows a direct correlation between better heat exchanger efficiency and reduced heating expenses.

In order to gain an in-depth knowledge of the performance of the present study, a comparison between the results and those of prior studies that examined the utilization of wastewater heat recovery systems in buildings is investigated. Table 3 compares the main indicators: energy saving, CO_2 emission reduction, and cost saving. According to the table, Golzar and Silveira [38], Bertrand et al., and Ni et al. [63] reported energy savings of 5 %-9%, 28 %-41 %, and 20 % without performing a comprehensive economic and environmental assessment. In comparison, the present work performed a comprehensive techno-economic-environmental evaluation, reporting a 10 % energy saving, an annual CO_2 emission reduction of 1.4 tonnes, and a cost saving of 24 USD/MWh. This comparison emphasizes that the present system provides moderate energy savings compared to the systems developed by Bertrand et al. [37] and Ni et al. [63]. However, the studied system stands out by effectively combining significant reductions in CO_2 emissions and substantial cost savings. This highlights its superior overall performance in improving energy efficiency and sustainability in building energy management.

Table 3
The comparison of the present system with previous studies investigated wastewater heat recovery systems for buildings.

Study	Energy saving	CO_2 emission reduction	Cost saving
Golzar and Silveira [38]	5–9 %	×	×
Bertrand et al. [37]	28–41 %	×	×
Ni et al. [63]	20 %	×	×
Present work	10 %	1.4 tonnes/year	24 USD/MWh

5. Conclusions

This article introduces a novel HVAC system to revolutionize smart residential buildings. The system consists of a dynamic control framework for energy use reduction and effectively supplies the energy production/usage/waste through smart component integration. The core of this concept is reusing the wastewater's huge heat potential for preheating the inlet air entering the air handling unit. The system's feasibility is assessed and compared with the conventional HVAC model comprising an energy wheel from all points of view. The hourly, monthly, seasonal, and annual indicators are assessed, and a sensitivity analysis is done to examine the system's viability thoroughly. In the following the concluding remarks and highlights are listed in detail:

- **Energy efficiency improvement:** The proposed system demonstrated a notable improvement in energy efficiency, increasing from 85 % in conventional systems to 95.4 %. This signifies a substantial decrease in primary energy use and a highly efficient thermal energy usage from wastewater.
- **Cost saving:** The suggested model's economic viability is revealed by the large reduction in the system's heating costs, which decreased from 54.9 USD/MWh to 30.7 USD/MWh. This reduction occurred despite the greater initial costs of 29,032 USD.
- **CO_2 emission reduction:** The proposed smart ventilation system achieved an annual reduction of 1.47 tonnes of CO_2 emissions, demonstrating its capacity to promote sustainability and diminish the carbon footprint of residential buildings.
- **Less reliance on district heating:** Throughout the winter, the system sustained elevated supply air temperatures, enhancing thermal efficiency and significantly reducing dependence on external heat sources. This consistent performance led to a substantial and continuous reduction in the building's overall space heating demand, contributing to energy savings and a more stable indoor climate. By minimizing reliance on additional heating, the system improved operational efficiency and promoted cost savings and environmental benefits through reduced energy consumption.
- **Economic viability:** The energy wheel, which accounted for approximately 50 % of the total investment cost, was vital in reducing energy use and enhancing thermal efficiency, hence justifying its higher price. The additional components, such as the thermal energy storage tank and heat exchanger, substantially affected the system's economic and operational efficiency.
- **Seasonal performance:** Seasonally, the energy wheel and wastewater heat recovery systems performed differently, producing less heat recovery in the summer and more in the winter. Regarding heat reuse efficiency, the energy wheel performed better than the wastewater system in most cases.
- **System integration:** Air handling units were integrated with radiators in a hybrid configuration to create a balanced and efficient heating solution. This approach ensures reliable primary heating and adequate ventilation, while radiators provide supplementary heating during periods of high demand. The hybrid system adapts to varying load requirements, enhancing thermal comfort and energy efficiency by dynamically distributing heat as needed across the building.
- **Sensitivity analysis:** The sensitivity study identified several key variables that substantially impact system efficiency. These include the number of households served, the temperature of wastewater exiting the tank, the performance of the heat exchanger, and the epsilon (ε) value of the energy wheel. Optimal system design and operation hinge on balancing these factors to maximize energy recovery and overall system performance. Fine-tuning these variables ensures the system can achieve both efficiency and reliability, adapting effectively to varying operational demands.

CRediT authorship contribution statement

Hui Liu: Writing – original draft, Visualization, Methodology, Investigation. **Zhe Du:** Writing – original draft, Software, Investigation, Formal analysis, Conceptualization. **Tingting Xue:** Writing – review & editing, Resources, Methodology, Investigation. **Tao Jiang:** Writing – review & editing, Supervision, Resources, Investigation, Funding acquisition, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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