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SURVEY OF THERMAL ENERGY RECOVERY AND REUSE TECHNOLOGIES IN MODERN HVAC SYSTEMS

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Abstract: HVAC systems have shown that they ought to make use of thermal energy recovery and reuse technology to increase the level of energy efficiency and minimise the impact of buildings on the environment. The systems greatly reduced heating and cooling needs and increased comfort levels in the region by absorbing waste heat from the exhaust air. The heat energy is reclaimed with the assistance of the state-of-the-art equipment, including rotary wheels, fixed plate exchangers, heat pipes and run-around systems, which in conjunction with the constant efficiency of 50-95%, transfer the sensible and latent heat between the airstreams. It also enhances their performance by incorporating IoT-enabled sensing, real-time monitoring, and intelligent control strategies. The ability to continuously control temperature, humidity, and airflow with the assistance of IoT sensors will enable automated ventilation adjustments, maximising performance and minimising energy consumption. Digital Twin technology is an appropriate tool for this model and enables predictive modelling, fault tolerance, and maintenance of the system's optimal behaviour throughout the building's life cycle. All these innovations combined with Building Automation Systems (BAS) and regulatory requirements can steer the HVAC designs to be reliable, comfortable to occupants and ultimately saving energy.

Keywords: Heat Recovery Efficiency, Thermal Energy Recovery, Heat Exchangers, HVAC Systems, Performance Indicators and Thermal Management Systems.

1 INTRODUCTION

In recent years, an increasing interest in sustainability in the environment has emerged, with the need to enhance energy efficiency in every sector, and HVAC (heating, ventilation, and air condition) systems are not an exception. A large percentage of energy used in commercial and residential buildings is attributed to HVAC systems[1]. Poor HVAC systems do not only add to the increased energy expenditure but also lead to the escalated greenhouse gas emissions and doubling the energy reserves[2]. The HVAC systems have been a major concern to building designers, owners and operators because of energy efficiency to minimize energy consumption and enhance the operation of buildings in a sustainable manner. In this regard, the construction of automation systems are critical in maximizing the energy consumption and attaining significant energy savings[3]. Advanced technologies are used to build automation systems, which control and monitor different building systems, such as the HVAC[4]. These systems are a combination of sensors, actuators and smart algorithms that will automate and optimize HVAC operation to provide a comfortable and energy-efficient indoor environment[5][6]. The main aim of establishing building automation systems is to reduce the energy wastage by adjusting the HVAC activities according to the actual needs of the building and the needs of the occupants.

In an optimal scenario, the HVAC system is supposed to work in consonance with the laid down standards of thermal comfort and at same time efficiency of system is maintained. Considering this perspective, it is crucial to use advanced diagnostic methods in order to evaluate HVAC systems' dynamic nature efficiently and consequently offer an accurate way to gauge system performance. The control method used in the installed system is more geared towards thermal comfort with minimal thought of system efficiency[7][8][9]. More research in this field is required as a preliminary measure towards establishing right control methodology of the system. The dynamic behavior of HVAC systems might be difficult to theoretically describe[10]. The system has several interacting elements that create a dynamic, nonlinear link between the input and output variables.

Even though these technologies have made great strides, there are still issues about how to integrate systems, their cost efficiency, upkeep, and getting them to perform well in different environmental situations[11][12]. Therefore, it is obligatory to conduct a comprehensive survey and define the most recent developments, evaluate their technical effectiveness, and mention new spheres of research and practice. The thermal energy recovery and reuse systems used today in HVAC systems, their principles, advantages, disadvantages, and future are broadly discussed in the current paper.

1.1 Structure of the paper

The present survey is structured as follows: Section II addresses fundamental concepts of thermal energy recovery and performance measures in HVAC systems, whereas Section III addresses technologies available to recover heat in rotary wheels, fixed-plate exchangers, heat pipes and run-around systems. Section IV is focused on the integration between thermal energy recovery and smart HVAC systems based on the usage of IoT, Digital Twins, and Building Automation Systems. In Section V, a compilation of related literature and recent studies is presented, and in Section VI, the key findings and future research directions are highlighted, concluding paper.

2 THERMAL ENERGY RECOVERY IN HVAC SYSTEMS

Energy recovery systems, also called total energy recovery systems, transfer both latent and sensible heat. The performance and efficiency of enthalpy devices for energy recovery are enhanced by the SES systems. Enthalpy devices recover more than 25% of the energy throughout the winter. Both sensible and latent heat are transferred via enthalpy or rotary wheels. They are widely used in HVAC systems because of their excellent efficiency, ability to manage humidity, and ability to prevent frost. However, because of their design, the airstream experiences a large pressure drop; In order to provide proper air circulation with a low pressure drop, powerful fans are fitted[13]. After more than 40 years of development, fixed plate heat exchangers (FPHEs) have emerged as the most popular kind of heat recovery system. Currently, the most often utilized form (around 89%) is cross-counter flow, which combines cross and counter flow.

2.1 Principles of Heat Transfer Relevant to HVAC

In order to lower demand for heating in residential buildings, heat recovery technologies have become increasingly popular in recent years. Sensible heat (energy) and latent heat (energy) are two categories of heat or thermal energy[14]. The sensible energy in exhaust air can be transferred to the supply air during the heating season, raising its temperature and lowering sensible heating demand for residential structure[15]. The majority of nations with cold climates have implemented building standards mandating a minimum sensible heat recovery efficiency, and most common type of heat recovery systems are those used only for sensible heat recovery[16]. Moisture in exhaust air can also be transferred to dry supply air when total energy recovery technologies are used.

A technique that is being utilized more and more to lower buildings' heating and cooling requirements is heat recovery. Depending on the building's needs, season, and the region, building exhaust air can be either a heat source or a heat sink. In order to raise the temperature of entering fresh air and lower the need for heating during heating season, the thermal energy in the exhaust air can be transferred[17][18]. The cooling demand can be decreased during the cooling season by using the exhaust air as a heat sink for the thermal energy in the warmer incoming fresh air[19]. Sensible heat is the dry air's recoverable temperature. The energy released by moisture in the air is known as latent heat. Sensible-only heat recovery devices are typically less efficient than total energy recovery devices, which are able to collect both sensible and latent heat.

2.2 Thermal Energy Flow in Commercial and Residential HVAC

Thermal energy recovery in HVAC systems is predetermined by a set of regulatory requirements and energy regulations that strive to enhance efficiency of ventilation and minimize total energy expenditure in buildings. These guidelines provide minimum benchmarks of performance of heat exchangers, the quality of insulation and the rates of ventilation to guarantee uniform and efficient recovery of energy. International and national standards, such as the ASHRAE requirements, green building rating systems and local energy codes, recommend hearth recovery ventilators and high-efficiency system environment[20]. These necessities, which demand performance testing, establish reasonable levels of efficiency, and good practice in system design, result in improved indoor air quality, reduced operating loads, and long-term sustainability. Together, these codes and standards are vital in hastening the implementation of more sophisticated heat recovery technologies in homes, business and industry.

2.3 Key Performance Indicators (COP, EER, Heat Recovery Efficiency)

The indicators used to evaluate performance of HVAC and energy recovery systems are COP, Energy Efficiency Ratio (EER) and heat recovery efficiency. A mix of such indicators controls the determination of equipment and performance.

2.3.1 Coefficient of Performance (COP)

It is important to enhance coefficient of Performance (COP) of mechanical vapor compression air-conditioning systems, which are consuming a lot of electricity, particularly where the air-cooled condensers are applied. The system can extract more heat by pre-cooling the air prior to entering the condenser coils to reduce condensing temperatures and minimize the compressor head pressure [21]. This reduces the compression services and power consumption. The evaporative media produce compressor run-time advertisement or misting sprayer water absorbing heat and cooling of air entering the evaporation process. This creates a cooler airflow which improves heat rejection, increases heat cooling ability and greatly increases COP with much less power consumption. The COP, like the EER, is another energy performance measure. Nevertheless, rather than quantifying useful output, it quantifies the heat transfer efficiency of an air conditioner or heat pump in terms of the electrical power needed. COP is calculated by using the amount of heat that a pump can generate per unit of energy that is used to run the pump: $COP = Q/W$, where Q is amount of heat or cooling produced by HVAC system and W is amount of energy used (in Watts). The energy performance and low operating costs are positively correlated with COP.

2.3.2 Energy Efficiency Ratio (EER)

The EER is usually a measure given to cooling systems. In essence, it determines the cooling output of a system using the electrical input of the system. The greater the efficiency ratio, the less electricity can be required to cool a building[22]. Use the following calculation to determine EER: EER rating = 10,000 BTU / 1000 W = 10. According to the aforementioned calculation, every watt of energy used has a cooling impact of 10 BTUs. EER is a standard measurement on the spec sheet of any HVAC system and a high-efficiency HVAC is one that has a value of more than 8.5 EER.

2.3.3 Heat Recovery Efficiency

The degree of heat recovery is a significant factor to which the capability of a heat exchanger to transfer sensible or latent heat between two streams of air at varying temperatures and pressures is determined. This metric is important in determining the performance, economic feasibility and environmental performance of energy-efficient HVAC and thermal management systems, which gives a clear overview of the entire system. Energy consumption decreases with higher recovery efficiencies, increasing system stability and improving indoor thermal comfort. The heat recovery efficiency is calculated along with other performance indicators, such as system compatibility, heat transfer rates, and pressure drop.

3 HEAT RECOVERY TECHNOLOGIES IN MODERN HVAC SYSTEMS.

Heat recovery is the term used to describe a device that transfers energy between two air sources at different temperatures. Put another way, it relies on using recovered waste heat to warm the air entering the inside. Sensible heat recovery and enthalpy recovery are two broad categories into which heat recovery systems may be classified. Because they can recover both sensible and latent heat, enthalpy heat exchangers have a greater sustainability effect because of the large percentage of wet load in the ventilation system and the requirement for indoor air humidity in modern buildings[23]. It is highly encouraging because heat recovery systems can now recover 60–95% of waste energy.

3.1 Rotary Wheel

The rotating porous wheel that powers rotary wheel heat recovery system is driven by a motor. The two streams alternate across the wheel during heat and moisture exchange, as seen in Figure 1. The rotor speed is typically modest, between 3 and 15 rpm. The overall efficiency of rotary wheel heat recovery is frequently significantly higher than that of any other air-side heat recovery system because of the nature of heat wheels, which allow heat transfer from the exhaust stream to the supply stream without passing through the exchange medium. A heat exchange efficiency of more than 80% is often possible with rotary wheel heat recovery[24]. For managing moisture carried by ventilation air, rotating wheel system has been shown to be one of the most effective methods. However, rotary wheel heat recovery only recovers around 40% of available enthalpy. The air mixing rate, rotation speed, wheel materials, and atmospheric conditions may all have a major impact on how well rotary wheel heat recovery works.

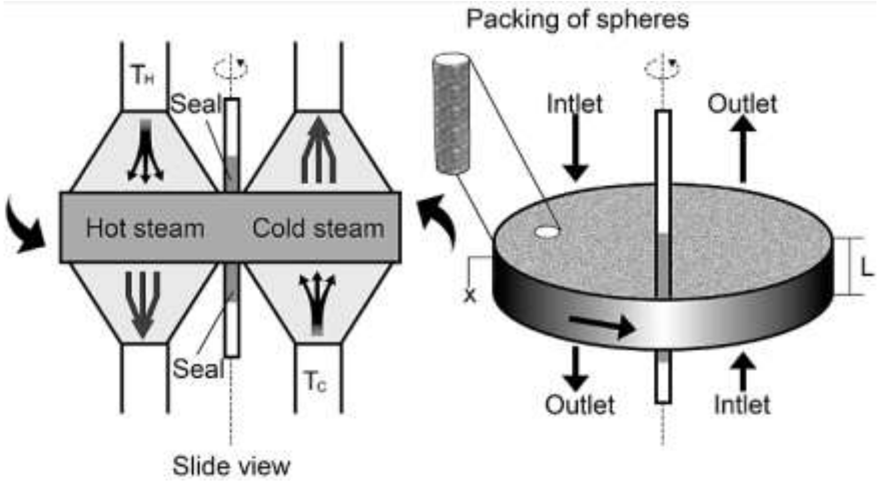

Figure 1: Optimal rotary wheel

3.2 Fixed-Plate

Fixed-plate heat exchangers are designed with stacked thin plates that create separate airflow channels, providing efficient transfer of both sensible and latent heat between exhaust and fresh air streams, as shown in Figure 2. Different flow arrangements, like counterflow, crossflow, and parallel flow, give the designers the flexibility in design and performance. The use of moisture-permeable materials enables these devices to operate as enthalpy exchangers, recovering both heat and humidity. Cutting-edge plate designs, such as microstructure and porous membrane cores, have demonstrated sensible heat recovery efficiencies in the 50% to 80% range. The development of plate materials and configurations has tremendously boosted thermal effectiveness with the current commercial systems being in the recovery rates that are quite high and suitable for residential applications.

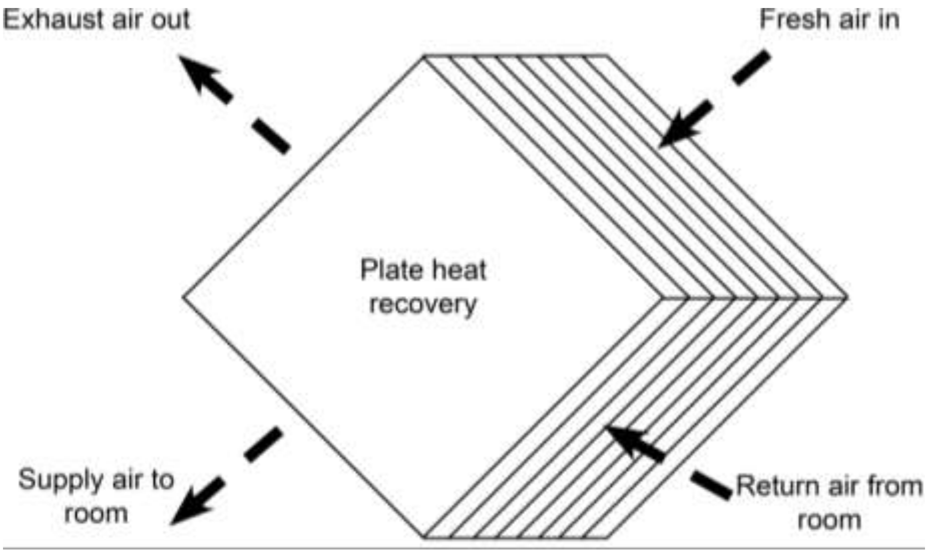

Figure 2: A fixed-plate heat exchanger

3.3 Heat Pipe

Heat recovery systems that use heat pipes transport heat between two solid interfaces by combining the concepts of phase change and heat conduction. The two closed tubes that make up a conventional heat pipe are filled with working fluid. With just a slight temperature differential, the heat pipe transports thermal energy from one side to the other. During operation, either gravity or capillary action in the wick carry the condensed liquid to the evaporation portion. The thermal efficiency of typical heat pipe exchangers is around 50%. Research has demonstrated that a naturally ventilated home's heat pipe recovery system may reach 50% efficiency with a pressure loss of less than 1 Pa[25][26]. The efficiency of heat pipes can be affected by the working fluid, the pipe configuration, the air velocity, and the temperature at the evaporator's intake[27]. As seen in Figure 3, several researchers have concentrated on the use of heat-pipe-type recovery over the past ten years, carrying out tests to evaluate its thermal performance and gather information on Heat-pipe systems' effectiveness in air conditioning applications for heat recovery. It demonstrates that the rate of heat transmission has risen to around 48% in both the condenser and evaporator portions.

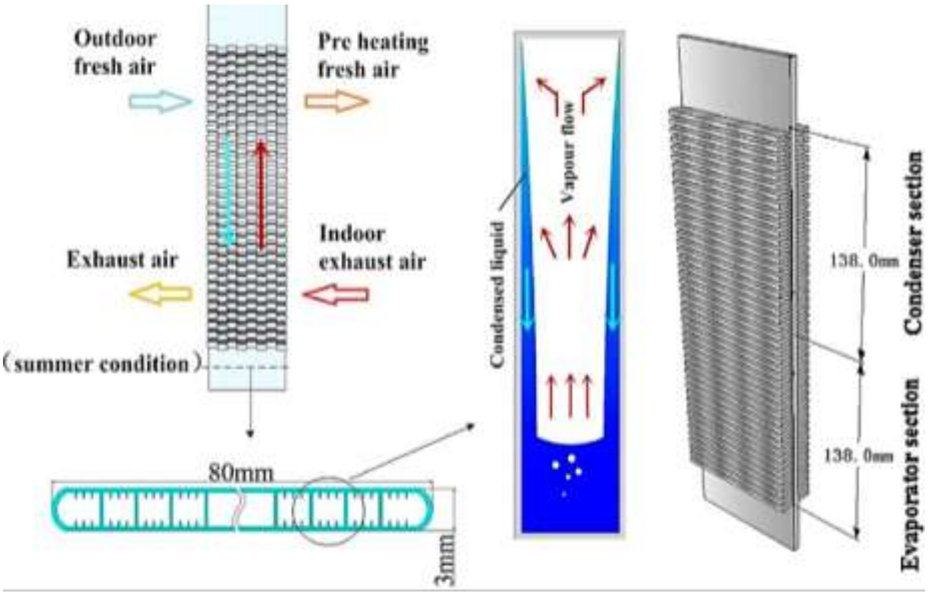

Figure 3: A micro-heat pipe recovery system

3.4 Run-Around

Run-around heat recovery systems consist of a coupling liquid and two distinct heat exchangers, as shown in Figure 4. The pump allows liquid to transfer absorbed heat between streams[28]. By keeping the two heat exchangers apart, run-around heat recovery may avoid cross-contamination. Under typical circumstances, heat exchange rate of run-around heat recovery is between 45% and 65%[29]. Installing a run-around heat recovery system can boost a building's ventilation airflow rate without consuming additional energy. Experimental results on the thermal performance of run-around heat recovery revealed that exchangers with a modest aspect ratio obtained the maximum overall sensible efficacy for a given total exchanger surface area.

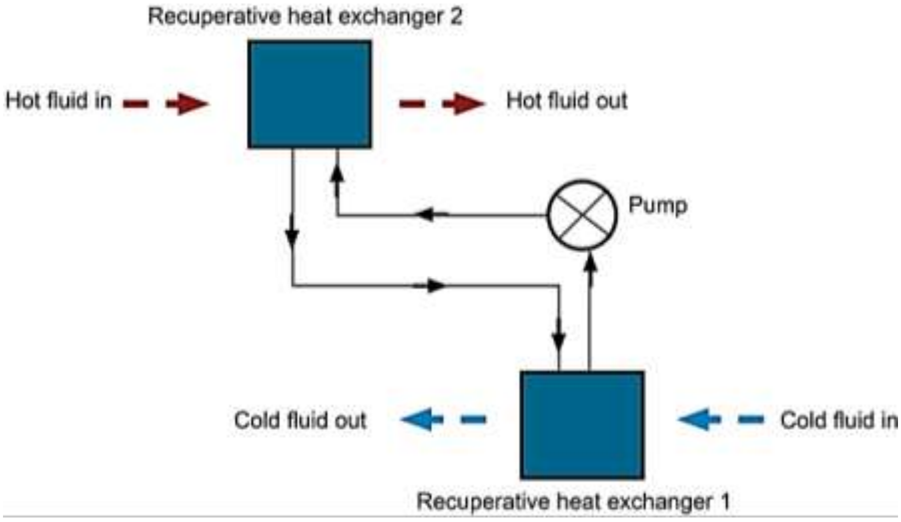

Figure 4: The working principles of run-around heat recovery

4 INTEGRATION OF THERMAL ENERGY RECOVERY IN SMART HVAC ARCHITECTURES.

Building automation systems (BAS) bring together devices such as communication networks, sensors, and controllers, to efficiently manage HVAC operations using smart technology, thereby maximizing energy use and indoor comfort. BAS allows regulating operations like ventilation, temperature, and fault detection which minimizes energy consumption and cost of operations and enhances system reliability.

4.1 Enhancing Monitoring and Control of an HVAC System through IoT

The Internet of Things (IoT) technology has a tremendous impact on HVAC monitoring and controlling by providing a real-time sensory mechanism, automation, and intelligent adaptation depending on indoor and outdoor environments[30]. The subsequent systems are used to ensure the occupants of a Passive House have the required thermal comfort using a minimum amount of energy: The mechanical ventilation heat recovery unit with the earth-to-air heat exchanger, and the air-duct electric heater[31]. The IoT sensors continually discuss temperature, humidity and airflow and can therefore indicate to smart controllers how best to operate and when to counteract inefficiencies[32]. Greater energy savings, reduced running expenses, and a constant degree of comfort will result from the combination. To sum it up, the IoT-enabled HVAC systems are not only the Passive Homes' most efficient and responsive but also the most sustainable.

4.2 Digital Twins' for Building Energy Recovery Optimization

Digital Twin (DT) technologies have become answer to optimization of energy performance and efficiency enhancement of the modern building system. They can help in real-time monitoring, forecasting analysis, and intelligent decision-making, and enable buildings to enhance energy flows, comfort management indoors, and managing operational needs [33]. The application of DTs in the fields of design optimization, energy simulation, enhancement of occupant comfort, and predictive maintenance, has shown their potential in making significant contributions to building energy performance[34]. However, challenges, which include lack of lifecycle integration, gaps in data acquisition and interoperability, still exist and most commonly arise when the utilization of DTs is founded largely on the BIM models. Nevertheless, these obstacles do not stop the development of DTs as efficient tools to model the thermal behavior, predict energy usage, and aid smart control techniques of the HVAC and energy recovery systems.

DTs for Sustainable Urban Systems, Net-Zero Goals, and Decarbonization

Digital Twin (DT) technologies are turning out to be the regulator of optimizing the energy performance and enhancing the efficiency of building systems of the present day. They help track energy flows, indoor comfort, and operating requirements in real time, predictively, and make smart decisions, making buildings even more effective at controlling these aspects[35]. It is demonstrated that the use of DTs has been utilized to achieve optimization of design, energy model, occupant comfort, and predictive maintenance, and could help achieve a major enhancement of building energy performance. Nevertheless, there are still some difficulties, such as insufficient lifecycle integration, gaps in the acquisition of data, and interoperability problems, especially when the use of DTs in the case of BIM models is maximum.

4.3 Integration with Building Automation Systems (BAS)

The Co-ordination of HVAC components, lighting, occupancy detection and energy management functions are enhanced by the Integrating of thermal energy recovery units and Building Automation Systems. BAS systems ensure centralized control, allowing automated regulation of ventilation rates and damper settings and heat exchanger operation based on the occupancy and environmental needs[36]. This synergy increases thermal comfort and reduces peak loads of energy and wastes of equipment cycling. Fault diagnostics and zone-to-zone performance benchmarking are also possible with BAS integration. This will result in more efficient, reliable and aligned heat recovery, which aligns with the building-wide optimization strategies [37]. Building automation and control systems (BACS) are the control systems that underpin these structures.

- **Sensors:** These sensors monitor environment, temperature, humidity, occupancy and light levels.
- **Actuators:** The physical elements of the building can be altered to react to the controlling system's cues, such as turning on and off HVAC equipment, opening or shutting dampers, or altering valves.
- **Controllers:** These are the BAS's brains, processing data from sensors and directing actuators. The controllers might be as simple as programmable logic controllers (PLCs) or as complex as computer-driven control systems.
- **Communication Networks:** BAS elements are connected to one another by wired or wireless networks. Communication protocols like BACnet, LonWorks, and Modbus facilitate the transmission of information between devices.
- **User Interface:** The interface also gives the operators an interface to communicate with the BAS. This might include computer graphical user interfaces (GUIs), touch panels, or mobile applications.
- **Control Algorithms:** These are collections of logic and rules that are built into the system to control how the BAS reacts to certain circumstances. Control algorithms are employed to maximize building system functionality so that inhabitants are comfortable and energy-efficient.

Role of Building Automation in Managing HVAC Systems

A key component of heating, ventilation, and air conditioning (HVAC) operations is building automation. There are a number of significant advantages associated with integrating BAS and the HVAC systems:

- **Energy Efficiency:** BAS streamlines the performance of HVAC systems to modify context in response to occupancy, real-time data, and outside variables[38]. This will make energy utilization more efficient, and less energy will be consumed.
- **Occupant Comfort:** Automation enables control of the indoor environment such as temperature and humidity with a high level of accuracy, which enhances comfort and well-being of occupants.
- **Remote Monitoring and Control:** The BAS has the ability to enable building operators to monitor and control HVAC systems remotely. This functionality enables fast fault resolution, effective troubleshooting and the execution of energy-saving strategies.
- **Data Analytics:** BAS gathers and interprets HVAC systems data, which provides useful information on the performance trends and equipment health as well as other optimization opportunities.
- **Fault Detection and Diagnostics:** Automation systems can detect anomalies and faults of HVAC equipment and maintain them in advance to minimize downtimes.

5 LITERATURE REVIEW

The section provides a close literature review of thermal energy recovery and energy efficient systems of HVAC. The emphasis is on the waste heat recovery technologies, intelligent HVAC innovations, and optimization of the system strategies. Table I provides a summary of the best practices according to study analysis and shows significant methodologies, performance findings and research trends in current HVAC energy recovery applications.

Barone *et al.* (2025) present an innovative and patented waste heat recovery system that enhance the energy efficiency of HVAC systems in railway coaches. The proposed solution uses an extra heating coil in HVAC to recycle the thermal energy of cooling loops of onboard electronic devices, operating temperature of which can be up to 50 C. To evaluate effectiveness of system, process of a real railroad coach was simulated in the MATLAB environment with a dynamic simulation model and was tested in three climatic conditions Almeraya (Spain), Naple (Italy) and Freiburg[39].

Lamrani *et al.* (2024) under consideration the detailed study of a Waste Heat Recovery (WHR) system with Thermal Energy Storage (TES) tanks. An appropriate lumped-dynamic thermal model was developed and tested against literature data to properly simulate the system's performance. The study examines the effects of various aspects, such as WHR effectiveness, TES type, PCM type, and TES volume, on system in a detailed parametric study. The findings show that reclaiming and storing of wasted heat in AC systems is a big boost to stability and performance of the systems. It is notable that, as WHR effectiveness of 0.55 to 0.85 rises, constant thermal power recovery period is not only raised, but water pump energy consumption is also low, and recovered water temperatures are high[40].

Tosin Michael Olatunde *et al.* (2024) discusses new tendencies and advances in the area of energy-efficient HVAC technologies, such as incorporation of renewable energy sources, intelligent sensors and actuators, and predictive maintenance algorithms. Such developments can further streamline energy performance, enhance the reliability of systems, and allow proactive control of HVAC systems, review highlights significance of energy-efficient HVAC technologies as one of building practices that make a building sustainable. In order to overcome present challenges and fully achieve promise of energy-efficient HVAC systems in assisting in the creation of a more sustainable built environment, research, innovation, and collaboration among stakeholders are still necessary. the constructed environment[41].

Pan (2023) examines and summarizes body of research on HVAC system energy-saving solutions, including passive, active, and intelligent energy-saving technologies, after an examination of HVAC system workflow and the causes of energy consumption. This study employs relevant energy-saving technologies to enhance the HVAC system in a targeted manner using a science and technology building built thirty years ago in southwest China as an example in order to better comprehend and use previously mentioned energy-saving technologies[42].

Bai *et al. (*2022) examines the various heat recovery systems used in homes, including cutting-edge approaches tailored to cold locations. The different technologies were compared using a variety of parameters. Frosting can occur in heat exchangers used in cold areas, reducing their efficiency. This review included defrosting and frosting prevention, among other frosting management techniques. Because existing frost control methods either damage indoor air quality or increase energy consumption, consequences of employing heat recovery for mechanical ventilation on indoor air quality were explored[43].

Farhat *et al.* (2022) The purpose of this study is to provide a comprehensive, up-to-date review of waste heat recovery (WHR) technology and uses, along with critical analysis and potential suggestions. Methods include Rankine cycles, thermoelectric generators, and heat exchangers. Additionally, Applications of WHR are looked at in the automotive sector as well as in residential and industrial areas. Studies show that significant energy savings may be achieved by improving heat recovery systems. On the other hand, one of the most popular research subjects at the moment is hybrid heat recovery systems. Future research should take backpressure's detrimental effects into account when recovering energy from engine and power generator exhaust gases, and hybrid systems should be given more consideration[44].

Table 1: Deep Learning- Based Predictive Demand Forecasting for Resilient Supply Chain Management

Reference	**Focus Area**	**Approaches**	**Key Findings**	**Objectives**	**Future Work**
Barone *et al.* (2025)	Waste heat recovery in railway HVAC systems	Patented WHR system using heat from electronic cooling circuits; MATLAB dynamic simulation; climate-based evaluation (Spain, Italy, Germany)	Recovered waste heat effectively increases HVAC energy efficiency; performance varies across climate zones	To repurpose dissipated thermal energy in railway coaches to improve HVAC efficiency	Extend testing to additional climatic regions; validate system using real-world railway operations
Lamrani *et al.* (2024)	WHR integrated with Thermal Energy Storage (TES)	Lumped-dynamic thermal modeling; validation with literature; parametric analysis of WHR effectiveness, TES/PCM types, TES volume	WHR effectiveness increase (0.55 → 0.85) boosts constant thermal recovery time; higher water temps; reduced pump energy	To analyze how WHR + TES improves energy stability and AC system performance	Explore optimal PCM combinations; examine long-term TES degradation; improve TES integration efficiency
Tosin M. Olatunde *et al.* (2024)	Emerging trends in energy-efficient HVAC	Review of renewable integration, smart sensors/actuators, predictive maintenance; system-level evaluation	Renewable HVAC integration and intelligent controls boost reliability and performance; emphasizes HVAC's role in sustainable buildings	To discuss innovations improving HVAC efficiency and sustainability	Encourage collaboration among stakeholders; develop advanced predictive algorithms; address integration challenges
Pan *et.al.* (2023)	Energy-saving technologies in HVAC systems	Review of passive, active, and intelligent technologies; case study of a 30-year-old building in China; targeted system upgrades	Combining multiple energy-saving strategies significantly improves performance in older buildings	To classify and demonstrate HVAC energy-saving strategies with a real-world example	Improve scalability of retrofitting strategies; test technologies in multiple building types
Bai *et al.* (2022)	Residential heat recovery	Review of HRVs/ERVs, frosting issues, frost	Frosting reduces performance; existing control strategies	To compare heat recovery methods and address	Develop efficient frost control methods without

	technologies (cold climates)	control strategies, IAQ impacts	either increase energy use or reduce IAQ	performance issues in cold regions	compromising IAQ or energy use
Farhat et al., (2022)	Systematic review of WHR methodologies & applications	Review of heat exchangers, Rankine cycle, thermoelectric generators; applications in automotive, residential, industrial	WHR optimization leads to major energy savings; hybrid WHR systems show high research potential	To provide a comprehensive analysis of WHR technologies and application domains	Address backpressure issues in engine exhaust recovery; further explore hybrid WHR system designs

6 CONCLUSION AND FUTURE WORK

Heat recovery efficiency is one of the main performance signs in today's HVAC systems, it allows the transfer of both latent and sensible heat from one air stream to another in a very efficient way thus reducing the energy consumption and improving the quality of indoor environment. These metric measures exchange of thermal energy and consequently supports in selecting, sizing, and tuning the operations of systems in both the residential and commercial applications. Research and Development in the fields of heat exchangers, their materials, and power controls have not only played a part in the rise of heat recovery but also contributed to making the use of such technologies a part of the green building practices. The governments and other agencies are putting more pressure on energy-saving and carbon reduction which is indirectly boosting the heat recovery technology market as the latter usually comes as a part of the high-efficiency category. Nevertheless, amongst the current technology, the performance greatly relies on factors such as the quality of installation, frequency of maintenance and how well the system has been integrated with the other HVAC components.

Future studies should concentrate on intelligent, sensor-based, and more sophisticated systems of heat recovery with better thermal conductivity materials and dynamic conditions control algorithms. In addition, these developments would be not confined to the integration with the renewable energy systems and hybrid HVAC architectures. They would still be capable of improving performance, lowering losses, and facilitating the use of sustainable building technologies of the next generation

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