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A Review-Based Assessment of Enhanced HVAC Efficiency for Sustainability

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ABSTRACT

This paper offers an in-depth review of current Heating, Ventilation, and Air Conditioning (HVAC) energy consumption patterns and techniques for enhancing efficiency sustainably. Principal outcomes reported from previous studies were categorized after an extensive literature review. From cost-effective measures like system tuning and zonal control systems to advanced methods like integrated greenery systems and passive solar design, the report addresses a wide range of solutions. The findings finally demonstrate the importance of smart technologies for energy management by pointing out their possible significant long-term savings. The study underscores the need to include energy-efficient technologies in building codes and standards in order to ensure that energy conservation remains front and center in new construction. The suggested conceptual framework combines several tactics to significantly reduce the consumption of energy, paving the way to a more sustainable

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future. This research is important for policymakers and all stakeholders aiming to efficiently design HVAC systems to enhance performance. Furthermore, the combined use of intelligent technologies with energy-efficient equipment is a vital research domain capable of achieving significant energy savings, therefore facilitating the achievement of predetermined efficiency objectives. By adopting these strategies, this study aims to highlight approaches to reduce peak demand during high consumption hours, thereby contributing to contribute in overall sustainable goals.

Keywords: HVAC systems, building energy consumption, energy efficiency, environmental sustainability, building automation.

Introduction

According to the estimation, up to 70 percent of the total energy consumption in buildings can be attributed to Heating, Ventilation and Air conditioning (HVAC) systems. Traditional HVAC systems, particularly Chillers have a widespread contribution in the electricity consumption and peak electricity demand. Clearly, there continues to be a challenge to find new strategies to reduce energy consumption in different parts of the building while maintaining the comfort and indoor environmental quality [1].

One viable approach involves integrating various components into a unified HVAC system. For example, direct evaporative cooling (DEC) systems are known for the cost effectiveness and for their efficiency for enhancing the thermal performance of cooling and ventilation while reducing energy consumption. In addition to that, by replacing the chlorofluorocarbons and hydro chlorofluorocarbons with water as a working fluid in DEC systems is also an alternative way of addressing the environmental Issues. Electricity consumption in buildings is characterized seasonal variations, directly impacting the demand and sustainability efforts. The peak energy consumption is heavily influenced by HVAC operations, such as ventilators and air conditioners, which are among the most energy intensive components in the building. The high energy costs incurred during peak load hours pose a significant challenge to effective energy management. Therefore, several strategies can help mitigate HVAC energy consumption during peak hours which offers cost savings and environmental benefits as well. Our study focuses on the challenges in to change the current HVAC usage by prioritizing the energy efficiency without compromising the sustainability. The key strategies include the passive design techniques, such as the use of programmable thermostats, zonal climate control, effective insulation, and mixed-mode ventilation systems which is helpful for minimizing the extreme heating and cooling requirements in residential buildings. In addition to that, smart devices and energy saving equipment play a crucial role in enhancing HVAC efficiency over the long term [2-6].

Our research aims to contribute to a broader understanding of how advanced technologies and innovative design approaches can optimize HVAC energy performance, ultimately supporting global sustainability initiatives.

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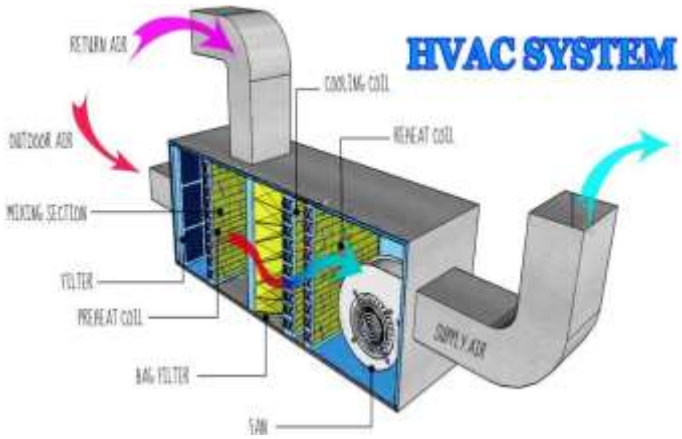


Figure 1: HVAC Process Diagram Energy

The significant energy share of HVAC systems in buildings drives academics to examine the different aspects of lowering energy consumption and identifying sustainable HVAC system solutions, which raise greenhouse gas emissions and expenses [8, 9]. Directly or indirectly, renewable energy sources could increase HVAC systems' sustainability. The utilization of different heating and cooling technologies that employ renewable energy sources in the building's HVAC systems is a crucial option for enhancing sustainability given the climate and geographic conditions. [7, 14, 16-18] Directly or indirectly, renewable energy sources could increase HVAC systems' sustainability. The utilization of different heating and cooling technologies that employ renewable energy sources in the building's HVAC systems is a crucial option for enhancing sustainability given the climate and geographic conditions.

The technologies used in HVAC systems in buildings are, Desiccant Heating, Ventilating, and Air- Conditioning systems [23-26], Biomass heating and cooling systems [30,31], Solar heating and cooling system (SHC) [27,28], Passive evaporative systems (PDEC) [6,7], Geothermal heat pumps (GHPs) [29], are all renewable technologies used in HVACs in buildings.

The HVAC systems of solar-powered decathlon homes built in the USA were examined by Ma et al. [9]. They discovered that the majority of them heated and cooled their spaces using heat pumps. Energy/heat recovery ventilators were used in over half of homes after 2005 to enhance HVAC efficiency. In the meantime, a number of additional technologies are used in HVAC systems to save electrical energy, including desiccant dehumidification, evaporative cooling, phase change materials, and nighttime radiative cooling.

We may be able to pinpoint the optimal parameters for lowering energy consumption via a variety of models for prediction to estimate energy consumption based on different characteristics in building and HVAC system designs [32-34]. When it comes

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to creating energy-efficient HVAC systems for buildings, modern integrated designs that incorporate programmed control systems are highly efficient [35-37].
Smart technology may be able to predict, respond, and adapt to changes in the weather, users, grids, and other factors. Utilizing these smart technologies in HVAC systems and buildings might significantly lower costs and energy consumption [8, 21].

HVAC System Energy Consumption Analysis
Air conditioning systems comprehend various components which includes heat producing units, cold producing units, air ducts, and air distribution systems. The outdoor unit plays a crucial role by generating the energy required for the cooling and heating processes for the components. Conditioned air or water is distributed through ducts, pipes, or ventilators. Proper maintenance of air emitting appliances, such as air coolers, air washers, and heat exchangers, is essential to ensure optimal air circulation. The heating devices that complete the HVAC cycle by distributing conditioned air within a building includes radiators, ventilators, fan coils, and floor heating systems.
For energy efficient technologies to operate in tandem within buildings, they must be integrated with other structural elements. Such integration is requisite for achieving low or zero emissions. Furthermore, the energy consumption in HVAC refrigeration cycles is influenced by operational duration, rated power and the load factors. Moreover, the conveyance systems, such as fans and pumps are account for approximately 60- 70% of HVAC related energy consumption.

System Simulation
HVAC System Energy Saving Technologies: This work examines energy-saving technologies in HVAC systems a n d categorizes them into three distinct approaches: passive, active, and intelligent. **Passive energy conservation:** It involves strategies that minimize energy consumption without relying on mechanical or electrical equipment.

Active energy saving:
E ncompasses technologies that employ mechanical systems, optimized equipment configurations, and strategic component selection to maintain the comfortable of both indoor environments and minimize the energy consumption.

Intelligent energy saving: Solutions leveraging advanced technologies such as computer networks, big data analytics, the Internet of Things, and artificial intelligence (AI) to enhance energy efficiency of building.
Building Envelope Design: The building envelope serves as a barrier between the indoor environment and external conditions, and influences temperature control and energy efficiency. Numerous studies have focused on enhancing the building envelopes to reduce energy consumption. Integrating vegetation into building designs has emerged as a key approach in urban planning, particularly in densely populated areas where green spaces are limited. Green facades and rooftops provides ecological benefits, such as improved insulation, mitigation of urban heat island effect, rainwater

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management, and enhanced air quality, and increased carbon dioxide absorption. Additionally, green building envelope enhances thermal insulation and optimizes heat transfer properties. This ensures minimal indoor temperature variations despite changes in outdoor temperatures, promoting human comfort. Therefore, designing effective building envelopes is crucial for reducing energy consumption and ensuring indoor environmental quality, safety, and comfort.

Passive solar heating and cooling technology: Passive solar structures are environmentally friendly buildings that utilizes the sun's radiant radiation for heating in the winter and cooling in summer. In order to maintain the stable indoor temperatures for a predetermined amount of time, these buildings exhibit exceptional heat storage capacity by using their structure to catch solar radiation. Considerable long term energy savings are realized, even with the initial outlay. Whereas solar energy is not commonly used for heating systems because of its erratic nature and poor density. To address this issue, researchers are investigating the development of solar assisted heat pump systems that integrate solar energy and heat pump technology. These systems offer several benefits, such as high energy usage, efficiency, cost effectiveness, and ease of implementation. Passive solar systems appear to be a promising solution for future energy conservation.

Active Energy Saving technologies

Inverter HVAC Technology: Frequency convergence and fixed frequency are the two design methods that an HVAC system can adopt. More often than not, the designs of frequency converters are used because they are more energy efficient compared with fixed frequency. The energy difference is that variable frequency drive (VFD) technology changes HVAC equipment speed, variable speed drive controls energy use in operations of fans, pumps, and chillers, particularly when varying load impacts on the system. Generally, it often saves use while adhering to energy savings guidelines arising from its adoption. Using this technology, it is possible to raise its efficiency up to 30%. Additional benefits includes lifespan and minimizes the maintenance costs, which makes it cost effective solution.

Natural ventilation technology: Natural ventilation utilizes the outdoor natural airflow for cooling and ventilation system components to reduce HVAC operational loads. It is designed using some approaches such as the use of operable windows, louvers, and vent stacks that allow cross ventilation and operation of the stack effect, which brings fresh air into circulation within the building. The entire concept revolves around allowing natural ventilation to occur primarily during the cooler days or in favorable climates making HVAC usage for cooling become minimal and hence reducing energy consumption. Moreover, utilizing materials possessing a high thermal mass also helps to regulate indoor temperatures. Other than that, the occupancy dependent controls further optimize energy use when there is sufficient natural ventilation, effectively utilizing energy consumption. At the same time, this gives an efficient way of improving the building economically as well as more environmentally friendly.

Thermal Storage System: Thermal Storage Systems (TSS) store cooling energy in low demand periods for later use during peak air conditioning hours. It has been used broadly in various applications. The chilled water storage tanks typically operates

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between the temperature ranges of 4-6°C, that are able to reduce peak cooling demand by 80-90% as compared with normal cooling methods. Studies also indicate that the thermal storage system generally does not save energy, but substantially reduces energy costs. As reported, that ice based thermal storage systems can lower cooling electricity costs by over 55%, despite energy savings overall being only about 5%.

Intelligent Energy Saving Technologies

Automatic Control Technology: It is a measure of advance automatic control over HVAC for resource conservation. Indeed, the existing sharp progress in high tech information and computer networks makes it more imminent to achieve an optimal integration of building structure, systems, services, and management for a more effective solution. Emerging trends, such as intelligent building control systems have ushered in perfect energy conserving automated measures and practices by minimizing electricity consumption and improving heat storage efficiency and resource use through integration of various sensors, controllers, and software platforms used in building automation technology. In this case, it is possible to deliver complete monitoring and management of buildings, enhancing energy efficiency, safety, and occupant comfort. Intelligent buildings, a global trend in architecture, enhance functionality while ensuring stable and comfortable living and working spaces.

Composite Building Energy System: Composite energy systems integrate multiple energy sources within buildings, improving energy efficiency through optimized equipment operation. They combine various energies to improve energy utilization diversity. By leveraging mass and energy flow data sharing, these systems achieve increased energy efficiency with a primary energy utilization rates of about 70-80%. Important aspects look like these: optimization of using different energy types, equipment integration, and progression of quite complex theoretical frameworks. Composite building energy systems, being interdisciplinary fields are still in the developing phase requiring further research and innovation to exploit their potential entirely.

Total floor area	8143.93m^2
Design level	Grade 2
Fire category	Class II high-rise office
Fire resistance	Grade 2
Height / floors	43.45m,10 above ground
Structure type	Concrete-frame shear wall

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Foundation	Prefab square pile
Service life	50 years
Waterproofing	Grade 2

Table 1: Overview of original appearance [39]

Mathematical Model

HVAC systems regulate heating, ventilation, and air-conditioning systems using temperature, humidity, and air quality to provide indoor comfort. Their efficiency and energy consumption are critical parameters of operational cost and environmental effect. This section examines the energy input, cooling output, and overall efficiency of an HVAC system's cooling coil. Co-efficient of performance:

COP = Input Energy (W)/ Useful Heating or Cooling Energy (Q)

Energy Efficiency ratio: EER = Electrical Power Input (Watts)/Cooling Capacity (BTU/hr). The energy balance equation for the cooling coil can be expressed as:

$Q_{in} - Q_{out} = deltaU$

Where Q_{in} is the heat input to the cooling coil from the refrigerant Q_{out} is the heat output from the cooling coil (to the air) $delta_u$ is the change in internal energy of the cooling coil. The air flow rate through the cooling coil can be calculated using: m = rho cV

Where: is the density of air is the volumetric flow rate of air.

HVAC System Engineering Cases

Project Case Introduction: he selected case study focuses on the rehabilitation of a science and technology building at an engineering institute in southwest China. In operation since September 1985, the building has been in use for over 30 years. Over time, the office infrastructure, fire safety systems, electrical facilities and communication and intelligent systems have become out- dated and no longer meet modern functional requirements. This project focuses on addressing these technical deficiencies while optimizing the limitations of indoor floor plan to enhance the building performance. [39]

HVAC generated the primary concern of this original structure at the first place. They are:

The building which is constructed using reinforced concrete frame shear wall structure, lacks thermal insulation in its envelope and hence creates very miserable thermal performance leading to uncomfortable indoor conditions. Split air conditioning systems with the outdoor units installed in an unorganized manner, impact negatively impacting the street facing facade havoc and raising safety concerns.

A water pump installed on the first floor generates low frequency noise, contributing to noise pollution that disrupts office workers in neighboring areas. During the winter season, fresh air supply is blocked by the closure of all doors and windows of the

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exterior. Which leads to unhealthy indoor air quality with excessive CO_2 levels and fatigue among occupants, due to poor air quality leading to reduced productivity. While some offices open windows, thus increasing energy consumption because of the added air conditioning load.
Figure 2: Original Building Plan [39]

Retrofitting measures

Passive energy saving technologies: Following the renovation, vertical greening was implemented on the east side of the building, creating a natural green barrier. This addition does not only enhanced the thermal performance of the building's envelope but also provided occupants with a visually appealing green landscape. Prior to the renovation, the building's north to south permeability and arc shaped design were strategically aligned with the summer wind direction, promoting airflow into the interior and enhancing natural ventilation. Post renovation simulation analyses indicated a significant improvement in indoor air quality, with natural ventilation frequency in primary functional spaces increasing to an average of 97.82%. These changes contributed to a marked enhancement of indoor temperature and humidity conditions.

Active Energy-Saving Technologies: The original air conditioning setup consisted of a split air conditioning system with disorganized outdoor units. Following the renovation, a centralized split air conditioning system featuring an air cooled heat pump was implemented. Additionally, technologies such as heat recovery, CO concentration monitoring, photo catalytic air purification, and PM2.5 filtration were integrated. These enhancements significantly improved indoor air quality and comfort.

Intelligent Energy-Saving Strategies: mart control system integration in buildings places a strong emphasis on enhancing energy efficiency through a variety of strategies. This includes intelligent conference room systems, automated lighting control, energy-efficient heating and cooling controls, and smart access control that combines time and attendance tracking. Additionally, the relationship between proposed extensions and existing structures was investigated using Building Information Modeling (BIM) technology. This approach has made it easier to create designs that are superior for window arrangements, external shading, and certain decorative components. Additionally, during the design stage, BIM was essential in identifying and resolving possible pipe collisions, guaranteeing correctness prior to construction. Furthermore, BIM technology enhanced the building's overall performance by supporting onsite construction procedures and streamlining long-term operation and maintenance management.

Summary

The goal of our work is to review approaches for modernizing aging infrastructure of a science and technology building that is thirty years old in order to increase sustainability, comfort, and energy efficiency. The retrofit used a mix of intelligent, active, and passive energy-saving technologies: Passive Measures: The building's exterior was vertically greened to improve natural ventilation and insulation.

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Analyses conducted after the repair revealed significant improvements in the thermal conditions and indoor air quality.

Thermal performance could be improved by upgrading the building envelope through passive measures. The goal was to minimize heat loss during winter and gain during summer by adding or upgrading insulation materials tailored to the building's location and climate. The airtightness of the building was critical in order to prevent unwanted air infiltration, which often occurs through windows, operable sashes, and roof openings such as elevator shafts and fire stairs. By stabilizing the temperature inside the building, these improvements reduce energy consumption for heating and cooling [40, 41].

An important aspect of the retrofit was replacing existing windows with high-performance units. The position, shading, and specification of these windows have been carefully considered in order to optimize solar heat gain and loss by seasonal requirements. Using high-performance glazing reduces thermal bridging and improves insulation, reducing heating and cooling loads while maintaining natural daylighting.

The retrofit incorporated passive solar principles by optimizing window location and shading mechanisms to regulate solar heat gain. This approach diminishes cooling loads in summer while permitting advantageous sunlight throughout winter, so enhancing energy efficiency and occupant comfort. The passive retrofit strategies for the science and technology building focused on improving the building envelope via enhanced insulation, airtightness, and high-performance windows, in addition to minimizing thermal bridging and optimizing solar gain and shading. These strategies conform to standards like Passive House EnerPHit for retrofits, seeking to provide enhanced thermal comfort, reduced energy consumption, and heightened sustainability. The incorporation of balanced ventilation with heat recovery additionally promotes energy efficiency while preserving indoor air quality. The application of simulation and modeling tools was crucial in customizing these passive measures to the building's unique conditions, promising significant energy savings and comfort enhancements [40-42] Active Measures: A centralized air-cooled heat pump system replaced the outdated split air conditioning system. Additional technologies that improved indoor air quality and energy efficiency included heat recovery, CO monitoring, photocatalytic air purification, and PM2.5 filtration.

Replacement or enhancement of HVAC systems with high-efficiency devices, encompassing heat pumps and variable speed (inverter) technologies, which dynamically modify operations to minimize energy usage while ensuring comfort. Modern HVAC control systems allow for automated temperature, occupancy, and air quality adjustments as well as real-time monitoring. Installation of new or recommissioned air handling devices with energy recovery ventilators that obtain heat from exhaust air in order to prepare incoming fresh air, thereby minimizing heating and cooling loads. Modernizing HVAC and ventilation systems with smart controls, increasing lighting efficiency, and utilizing energy monitoring and management tools to dynamically improve building performance and occupant comfort are the main active energy-saving technologies in these retrofits [44- 46].

Intelligent systems: Access control, heating, cooling, and lighting ll are equipped with smart controls. In order to improve designs, identify possible construction problems, and enable effective operation and maintenance, Building Information Modeling

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(BIM) was used.

To assess important environmental factors like temperature, humidity, CO_2, and volatile organic compounds (VOCs), the retrofit used wireless, battery-free sensors that were driven by energy harvesting devices (such solar cells or temperature differences). These sensors allow for flexible installation without the need for wiring or upkeep, allowing for thorough or progressive retrofits with little disturbance. Using open protocols like BACnet-IP and KNX, this wireless sensor technology enables smooth integration into current Building Management Systems (BMS), assuring scalability and compatibility [47, 48].

Radio-controlled valve actuators, which use energy captured from temperature gradients to modify radiator output based on real-time conditions, were used to implement intelligent heating control. This maximizes heating efficiency without the need for costly rewiring or battery replacements [47]. Additionally, IoT sensors and AI-driven algorithms are used to dynamically regulate HVAC systems, which modify ventilation, heating, and cooling in response to changes in occupancy and the surrounding environment. This reduces energy waste while preserving occupant comfort [50].

Smart meters and energy management platforms that continuously track energy usage, identify irregularities, and facilitate predictive maintenance were integrated into the retrofit. This data-driven strategy contributes to energy savings, device longevity, and resource optimization. Intelligent systems assist sustainability goals and legal requirements by monitoring ESG (Environmental, Social, and Governance) objectives and compliance parameters [49, 50].

Without requiring major construction, these smart retrofit techniques offer a cost-effective, minimally intrusive means of rapidly modifying building infrastructure to satisfy strict energy performance standards. According to case studies, integrating intelligent systems can result in energy savings of more than 50%; certain integrated system retrofits have been shown to reduce energy use by up to 84% when compared to baseline settings. Long-term sustainability and adaptability are ensured by the wireless, intelligent systems' scalability and flexibility, which provide phased implementation and future enhancements [47, 51, 52].

Thermal Comfort: Thermal comfort is the mental state that reflects satisfaction with the thermal environment [59, 60]. Thermal comfort cannot be measured by a range of degrees. Realistic intra-hour balanced load signals analyze HVAC load characteristics under changeable exterior and internal temperatures [58]. The optimal temperature set-point schedule minimizes operational costs, CO2 emissions, and occupant thermal discomfort [61]. Residential buildings, offices, hospitals, and universities experienced optimal thermal comfort due to factors such as convective heat, air velocity, air temperature, humidity, garment insulation, and physical activity. The building's HVAC system consumes the most energy. A plan, orientation, and design can improve building energy and temperature problems. Thermal comfort is undervalued in many businesses with high employment prospects. By employing various technologies, we can increase thermal comfort and conserve more energy [58]

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Conclusion

This research underscores the need for action of reconsidering the consumption of energy in HVAC systems to advance sustainable and eco-friendly building practices. Research indicates that an effective combination of passive, active, and intelligent energy-saving strategies improves energy efficiency while maintaining residential comfort and air quality. Approaches including smart building controls, centralized air-cooled heat pumps, and vertical greening have continually demonstrated promising in lowering operating expenses and consumption of energy. Additionally, the use of Building Information Modeling (BIM) is becoming more widely acknowledged for its capacity to facilitate accurate design and efficient construction management. When taken as a whole, the data supports a long-term shift toward sustainability in the built environment by arguing for the inclusion of such strategies in contemporary building standards and norms.

CRediT authorship contribution statement

Fahad Khan Khalil, Ibad Ali Khan: Conceptualization, Methodology, Writing-orignal draft, Visualization, Investigation and Softwares. Abdul Wasay, Zaheer ul Islam, Israr ul Hassan, Leixiaoyu : Resources, Writing Reviewing and editing.

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Data availability

Data will be made available on request.

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