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Solutions to Achieve High-Efficient and Clean Building HVAC Systems

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Abstract: The building sector accounts for a substantial amount of energy consumption, resulting in higher carbon emissions and environmental impact worldwide. Electrification and energy efficiency in building systems can be the key to decarbonization in buildings. This research proposes new heating and cooling loops consisting of heat pumps to lower natural gas usage in building systems. Typical chillers and boilers in the cooling and heating loops are replaced with heat pumps to serve the loads and maintain thermal comfort in the building. In addition, a new optimal supply air temperature (SAT) reset strategy is also implemented with the proposed configuration for better system performance. A large multi-zone office building is simulated as a case study to measure the conventional system's electricity and natural gas consumption and the proposed design. Even with heat pumps that use electricity as the energy source, electricity consumption is reduced by 3.3% to 11.8% in different climate zones for the proposed system. On the other hand, 10.2% to 67% lower natural gas is consumed when the proposed system and the optimal SAT reset are utilized. The carbon emission is also reduced by 10.8% to 38% compared to the conventional system. The results show that the proposed design and optimization strategy can lead to significant energy and cost savings in conjunction with lower carbon emissions.

Keywords: energy efficiency; decarbonization; electrifying; cost-effective; HVAC system

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1. Introduction

Rapid population growth and urbanization have led to a major expansion in the building sector worldwide. The development in the building sector has also resulted in increased energy demand, whereas the production sources remain nonrenewable and limited. Fossil fuels (oil, coal, and gas) account for almost 90% of the primary energy production globally and are a major contributor to greenhouse gas (GHG) emissions [1]. As a result, buildings account for almost 40% of energy consumption and about 30% of greenhouse gas emissions [2]. Therefore, measuring and reducing energy inputs in buildings is critical to minimizing environmental impact [3]. It has been shown in different studies that increasing the energy efficiency of the building systems can be an effective way of decreasing energy input in buildings. Although efficient systems can increase the initial cost of the building, it eventually saves energy costs and reduces carbon emission.

Operational energy services that include heating, cooling, air conditioning, lighting, equipment, appliances, etc., account for almost 80% of the energy consumption in the lifecycle of the building [4]. HVAC (heating, ventilation, and air conditioning) systems contribute to more than half of that energy usage. Therefore, designing these systems to minimize energy consumption and achieve better energy efficiency has become imperative. Several studies have recently focused on optimizing the efficiency and operation control of HVAC systems. For example, Lam [5] conducted a parametric analysis of office buildings considering building load, HVAC system, and plant for appropriate energy conservation measures [5]. Improving the system control and parameters for maximum energy efficiency

was also studied where major retrofit cannot occur [6]. Some studies focused on optimizing either the optimization of the configuration of systems [7,8] or operational parameters (such as supply air temperature, chilled water temperature, etc.) to achieve better performance of the systems [9–11]. Due to the recent development of combined heating and cooling systems, some studies are integrating these systems to mitigate adverse environmental impacts [12,13].

Energy efficiency methods can help to minimize carbon emissions by lowering energy use. Many studies have demonstrated that upgrading buildings may cut energy usage and, as a result, carbon emissions dramatically. For example, Galvin et al. [14] discovered that upgrading commercial buildings in the United Kingdom might lower carbon emissions by 17–30%. Tang et al. [15] discovered that upgrading residential structures in China might cut carbon emissions by 17–33%. The cost-effectiveness of energy-saving measures is determined by the cost of the retrofit as well as the quantity of energy saved. Numerous recent studies have looked at the cost-effectiveness of energy-saving methods. Vázquez et al. [16], for example, assessed the cost-effectiveness of upgrading public buildings in Spain. The study discovered that retrofitting was cost-effective for many buildings, with a payback period ranging from 8 to 14 years. In a similar vein, Wang et al. [17] investigated the cost-effectiveness of upgrading residential structures in China.

The utilization of modern technology such as smart building systems, building automation, and energy storage are recent breakthroughs in energy retrofitting strategies. These technologies can increase the efficacy of retrofitting methods while shortening the payback period. Kim et al. [18], for example, assessed the efficacy of retrofitting commercial buildings in South Korea with building automation and energy storage technologies. According to the study, retrofitting is cost-effective, with a payback period of three to five years.

Previous studies mostly focused on the waterside of the HVAC system in commercial buildings and reported encouraging results, but the majority of them lay emphasis on chillers as the primary energy user in chiller plants. Even if other interacting components (e.g., pumps and fans) are considered they only employ simplified first-principles models that ignore the operating complexity of these components. Most of these gaps are addressed in a recent study by Fathollahzadeh et al. [19], which finds that flexible cooling demand combined with non-linear component models for electric demand minimization of the waterside HVAC system in commercial districts can result in higher savings than rigid demand. A review of the published literature finds that only a few research studies focus on the airside optimization of district-scale HVAC systems, and no study combines the air- and water-side of the HVAC system for commercial districts. The airside of the HVAC system can account for up to 20% of the building's electric energy consumption. Furthermore, when both the air- and water sides of the HVAC system are adequately coordinated, there may be possible synergies [20].

One study gap is the lack of long-term evaluation of retrofitting measures' efficacy. While short-term studies have yielded encouraging results, further study is required to assess the long-term effects of retrofitting methods on carbon emissions reduction and cost-effectiveness. For example, Pye et al. [21] examined the influence of energy retrofitting techniques on carbon emissions reduction in the United Kingdom. The study discovered that retrofitting methods lowered carbon emissions by 27% in the near term. However, the long-term impact remained unknown.

Most commercial buildings in the US employ variable air volume (VAV) systems for heating and cooling purposes. This type of system varies the air supply from the air handling unit (AHU) according to the zone load requirements to maintain thermal comfort. Chilled water VAV systems with air or water-cooled chillers and gas-fired boilers are relatively common in large buildings in the US. Although these typical system arrangements can efficiently reduce overall energy consumption, they cannot eliminate burning fossil fuels. Eventually, they lead to higher carbon emissions and negative environmental impacts. Therefore, some studies have focused on electrifying several system components and

decarbonizing the building sector. Heat pumps for heating and cooling purposes of buildings have recently gained popularity due to their potential for electrification and decarbonization of buildings. Heat pumps are electrical devices that convert thermal energy from external sources (air, water, etc.) to useful heat for space heating and cooling purposes [22]. Research in different countries has demonstrated that heat pumps are superior alternatives to maximize efficiency and minimize carbon emissions, reporting up to 50% emission reductions [23,24]. However, there remains a significant scope of research to employ heat pumps appropriately instead of the typical system arrangements and study their performance.

Additionally, the hot water loop also serves the VAV box reheat coils for any local reheat requirement. The boilers generally use natural gas as the energy source. Therefore, it can be observed that there are two separate loops for cooling and heating when a typical HVAC system is considered with two individual coils.

Several configurations have been proposed consisting of chilled water VAV systems with air-cooled chillers, and heat pumps to reduce energy consumption and improve the performance of typical cooling heating loops. However, there remains a valuable scope for research advancement for energy savings and sustainable design configurations. This paper selects one configuration consisting of air-sourced heat pumps to analyze and evaluate this arrangement's benefits. This proposed configuration presents a new arrangement of heating and cooling loops with the air handling units (AHU) that consist of air source heat pumps instead of chillers and boilers. The proposed approach also suggests the improvement of AHU's coils and the system's overall operation to minimize energy consumption and maximize efficiency and cost savings. In addition, a new strategy for optimizing the supply air temperature (SAT) is implemented with the proposed configuration that differs from the SAT reset recommended in ASHRAE Guideline 36 [25]. Three scenarios with a typical chilled water VAV system design, proposed configuration, and optimal supply air temperature reset in the proposed configuration are simulated in a multi-zone case study building to evaluate the energy performance. The annual electricity and natural gas consumption are compared in different climate zones among the three cases to demonstrate the benefits of the proposed configuration with the optimal supply air temperature reset.

Thus, this research considers the prospective use of heat pumps for space heating and cooling purposes, replacing the conventional components to achieve electrification and decarbonization of buildings. A typical chilled water VAV system is considered the baseline system for this research. Figure 1 depicts commonly used chilled and hot water loop setups for chilled water VAV systems. Here, a cooling coil is connected to air-cooled chillers, which serve the cooling load in a building through multiple air handling units (AHUs). Similarly, for the heating loop, the heating coil is connected to boilers to meet the heating load of a building.

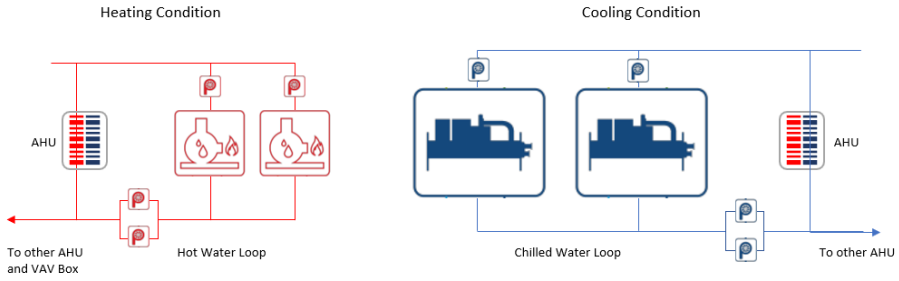


Figure 1. Typical cooling and heating loop configurations with two chillers and boilers.

Moreover, the carbon emission for the proposed configuration is also calculated to evaluate the system's environmental impact. The novelty of this research lies in creatively integrating the heat pumps with existing heating and cooling loops that can efficiently reduce energy usage and the cost of the operation. The proposed arrangement also utilizes

fewer resources upfront and shows the long-term benefits of reducing the use of fossil fuels in building systems.

2. Research Methodology

The study's goal is to offer a novel configuration for variable air volume (VAV) systems that can assist decrease energy costs, encourage electrification, and reduce environmental impact. The researchers began by performing a thorough literature analysis to discover existing HVAC system setups and optimization methodologies.

The paper suggests a novel configuration for VAV systems based on a literature assessment that employs a single coil for both heating and cooling, decreasing pressure drop and operational expenses. Air-source heat pumps, which can replace part of the chillers and boilers for higher efficiency in cooling-dominated regions, are also included in the setup. A control sequence is then created to guarantee the effective functioning of the suggested arrangement, which switches between heating and cooling modes based on the outside air temperature (OAT). The supply air temperature (SAT) is additionally reset using a trim-and-respond algorithm that considers the number of zones in cooling or heating at any one moment, rather than merely the OAT.

The researchers used simulations and models to conduct an energy study to evaluate the energy efficiency of the suggested design and control sequence. The findings show that the suggested architecture and control sequence can minimize energy consumption and operational expenses while boosting electrification and reducing environmental effect. Overall, the study believes that the proposed design and control sequence can provide considerable advantages to building owners, occupants, and the environment, and it advises more research to improve and refine the system.

2.1. Proposed Configuration of VAV System

The proposed configuration of the VAV system is shown in Figure 2. The standard VAV system's air handling unit (AHU) consists of two coils fed by two separate loops. However, both coils do not heat and cool simultaneously in the AHU. Only one coil is active at a point in time, depending on the heating and cooling loads of the zones. Therefore, chillers and boilers are connected to one single coil for operation. This will lead to a lower pressure drop across the AHU and a lower operational cost. In addition, the suggested approach will lower the initial cost of the HVAC system of the building as it only uses one single coil. It will also provide a cost-effective approach to electrifying the buildings. Saving money on HVAC system initial costs and operating expenses allows more money to flow into other areas of the economy and makes building costs more reasonable for construction [26].

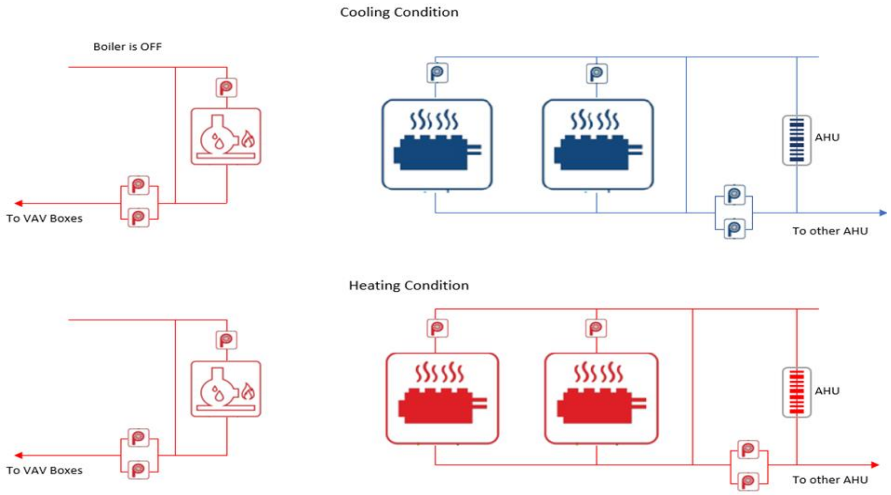


Figure 2. Proposed cooling and heating loop configurations with one coil (two HPs and one boiler).

Secondly, air-source heat pumps can be utilized instead of all of the chillers and some of the boilers for the proposed configuration. Heat pumps can serve the heating and cooling loads in a building according to zone requirements. Unlike chillers and boilers, heat pumps transfer thermal energy, so they can run in any mode as required. Due to this, the heat pumps are connected to the coil in AHU instead of chillers for the cooling loop, as shown in Figure 2. Moreover, the boiler for system-level heating is also replaced with heat pumps. In this research, the configuration focuses on the system heating and cooling loops. Therefore, the zone local reheat arrangement remains the same. The heat pumps have a higher efficiency than chillers in cooling-dominated climates, reducing energy consumption compared to a typical arrangement. In heating-dominated climates, dual-fuel heat pumps can be utilized to tackle the situation when the heat pump's efficiency drops. For a lower supply air temperature setpoint, the system heating can also be shifted to local reheat, reducing the load on heat pumps that are not efficient. This can minimize the strain on the coil while keeping the energy consumption limited. Additionally, as some boilers can be replaced with heat pumps for the proposed configuration, it paves the way to reducing natural gas usage on site. Therefore, the proposed configuration can lead to long-term benefits in terms of electrification, operational cost, and environmental impact.

Control Sequence

A control sequence is also designed for the proposed configuration to ensure the system's efficient operation. As only one coil is connected to the heating and cooling loops, the heating and cooling control depends on the outdoor air temperature (OAT). When the OAT falls below 45 °F (7.2 °C), the system loop shifts from cooling to heating; hence the cooling sources should be turned off. Once the OAT exceeds 50 °F (10 °C), the loop switches from heating to cooling; thus, the heating sources should be turned off. A dead band of five degrees can be used to avoid cycling between cooling and heating. The supply air temperature control loop may be the same as in a standard VAV system with two coils. The only difference is that the same coil is controlled in cooling or heating mode, and the loop in each AHU servicing this single coil should be available in heating or cooling mode, depending on the OAT. The SAT resetting algorithm may be the same as in a standard VAV system. However, during the heating period, the supply air temperature setpoint may be modified upward or downward to evenly distribute the heating loads between the system and reheat loops, such that the heating load is moved from the coil to the VAV box or vice versa. The principal benefit of this system is that each AHU uses one coil rather than two coils, resulting in smaller AHU size, fewer piping and control valves, and lower fan energy usage owing to reduced flow resistance. This setup also does not require a preheat coil. This shows how the proposed configuration can contribute to the reduction of initial and operational costs of the building.

2.2. Proposed Supply Air Temperature (SAT) Reset Strategy

ASHRAE Guideline 36 recommends that the supply air temperature is reset linearly between a fixed minimum value (e.g., 55 °F or 13 °C) and an adjusted maximum value as a function of outside air temperature (OAT). The maximum value is adjusted with a trim-and-respond algorithm to keep the cooling control signal lower than a predetermined value, such as less than 95%. However, resetting the SAT as a function of OAT may not be the best strategy as there may be zones in cooling even during colder seasons. As a response, Nassif [27] has proposed using zone heating or cooling control loops to reset the supply air temperature. In this strategy, the number of zones in cooling or heating at any time is counted, and the zone value is assigned to be 1 (one) if the zone is in a cooling or dead band. The zone value is set to be 0 (zero) otherwise. The resetting cooling signal (RCS) is then calculated based on the zone value, design ratio, and the sum of the zone air flow rates (Figure 3). The SAT is reset based on RCS instead of OAT. This method can balance the fan power and heating requirement efficiently, unlike the strategy in Guideline

36, and lead to energy savings in different locations. Therefore, this SAT reset strategy is implemented with the proposed configuration of the VAV system for energy analysis.

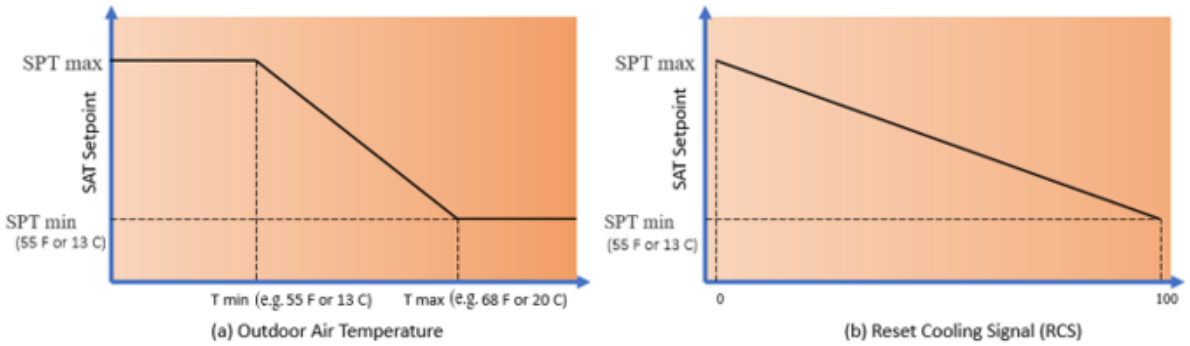


Figure 3. SAT setpoint (SPt) resetting strategies (**a**) Guideline 36 and (**b**) recommend.

3. Simulation & Analysis

3.1. Case Study of a Multi-Zone Building

A multi-zone building is selected as a reference and simulation to evaluate the energy consumption of the typical systems and proposed configuration. It is a four-story office building model with a total area of 160,000 ft^2 (14,864.5 m^2), where each floor has five zones (Figure 4). The window-to-wall ratio is 40%, and all of the other envelope constructions are according to ASHRAE standard 90.1 and default eQuest materials set up for a mid-rise office building [28].

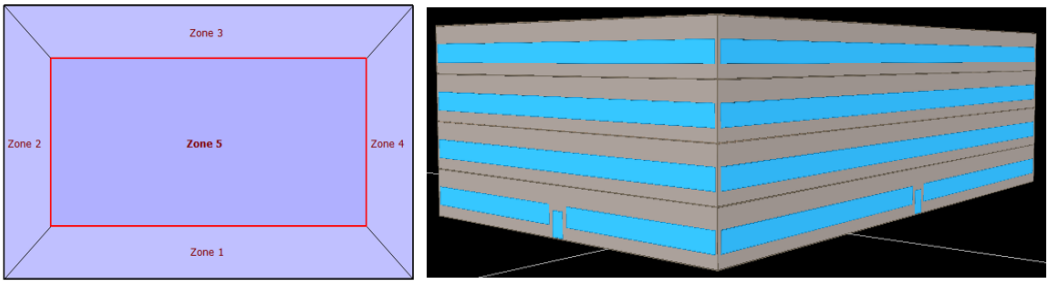


Figure 4. Building geometry and thermal multzone for each floor.

The design air flow rates are calculated according to the cooling loads, and occupancy is calculated according to standard office spaces. The building is assumed to be occupied weekly from 8 am to 6 pm. The chillers, boilers, and heat pumps were sized according to the hourly loads of the zones of this building. Two 300 tons capacity chillers can serve the cooling load of the building. Three scenarios are then simulated for the case study building's annual electricity and natural gas consumption. The first scenario is the typical chilled water VAV system with air-cooled chillers. The second scenario is the proposed configuration with one coil and two heat pumps replacing the chillers and boiler. The last scenario is the optimal SAT reset strategy implemented with the proposed configuration.

3.2. Location and Climatic Analysis

To evaluate the impact of each proposal scenario on energy usage, nine cities based on ASHRAE climate zones are chosen, representing a diverse variety of climatic conditions from various continents and both hemispheres. Orlando (FL), Austin (TX), Phoenix (AR), Los Angeles (CA), Charlotte (NC), Cincinnati (OH), Seattle (WA), Boston (MA), and Fargo (ND), have been chosen for simulation and analysis. Their respective climate zones and heating and cooling degree days are shown in Table 1 for better understanding.

Table 1. Locations and climate zones in the USA.

City	Climate Zone	Heating Degree-Days	Heating Degree-Days
Orlando (FL)	2A	544	3379
Austin (TX)	2A	1654	2989
Phoenix (AR)	2B	941	4557
Charlotte (NC)	3A	3081	1669
Los Angeles (CA)	3B	1284	617
Cincinnati (OH)	4A	4754	1151
Seattle (WA)	4C	4729	177
Boston (MA)	5A	5621	750
Fargo (ND)	7A	8793	553

3.3. Carbon Emission Calculation

Different carbon multipliers exist in the ENERGY STAR Portfolio Manager Technical Reference for Greenhouse Gas Emissions [29]. The carbon multipliers for electricity and natural gas are found in the selected climate zones. Once the case study building is simulated and annual electricity and natural gas consumption are calculated, the total annual carbon emission (Kg CO_2 e) can also be calculated with these multipliers for each location. For natural gas in the United States, these data are derived from the Federal Register factors connected with the Environmental Protection Agency's (EPA) Final Rule for Required Reporting of Greenhouse Gases, and all variables are applied to your site's energy usage in MBtu. Emissions from electricity generation are measured directly at power plants, which transmit continuous emissions monitoring system data to the EPA. These data are gathered in the United States Environmental Protection Agency's Emissions & Generation Resource Integrated Database (eGRID). Based on the location and zip code, all criteria are applied to the building. This can show the environmental benefits of the proposed configuration and optimal SAT reset in terms of carbon emission for each scenario. Table 2 shows the electricity and natural gas carbon multipliers for the nine locations in the RFCE eGRID subregion from the Energy Star Portfolio Manager [30].

Table 2. Carbon multipliers for selected locations in the USA (Kg.CO2e/Mbtu).

Location	Electricity	Natural Gas
Orlando, FL	124.45	53.11
Phoenix, AZ	136.60	53.11
Austin, TX	124.44	53.11
Los Angeles, CA	66.29	53.11
Cincinnati, OH	156.07	53.11
Seattle, WA	85.53	53.11
Charlotte, NC	99.37	53.11
Boston, MA	70.13	53.11
Fargo, ND	166.06	53.11

4. Results

4.1. Seasonal Cooling/Heating Electricity and Fan Power Consumption for the Proposed Configuration

Three cases were simulated to show the proposed configuration's daily cooling, heating, and reheat loads plus fan power on the hottest day in summer, the coldest day in winter, and a mild day during spring. The first case consists of a typical chilled water VAV system with two air-cooled chillers and two gas-fired boilers. The second case is the proposed configuration, where two air source heat pumps of the same capacity as two chillers are employed with a single coil. In this scenario, the supply air temperature is reset linearly between 55 to 65 °F (12.8 to 18.3°) and outdoor air temperature (OAT). The third case is the proposed configuration with the new supply air temperature reset algorithm

described in Section 2.2. The three scenarios are simulated in Cincinnati, OH, to evaluate the proposed configuration's benefits.

Figure 5 shows the proposed design with optimal SAT has significant savings of 29% from the common design in heating mode during winter. In terms of cooling loads, the proposed design shows a 16% reduced consumption during Spring and similar consumption in Summer. Figure 6 demonstrates an increase of 17% in reheating loads that occurs during Winter due to the proposed SAT reset. However, the reheat in Spring is reduced by 69%, and the reheat in Summer is eliminated due to the proposed SAT reset, which shows the potential savings that can be obtained with the proposed system. In this case, it can be observed that a boiler heats only around 20% of the VAV box coil, so there is less natural gas consumption due to SAT setpoint strategy. Figure 7 shows the change of supply air temperature in all three cases for the common system and the proposed optimal system. It can be observed how the SAT is varied in the proposed case to reduce the building's cooling and heating energy consumption.

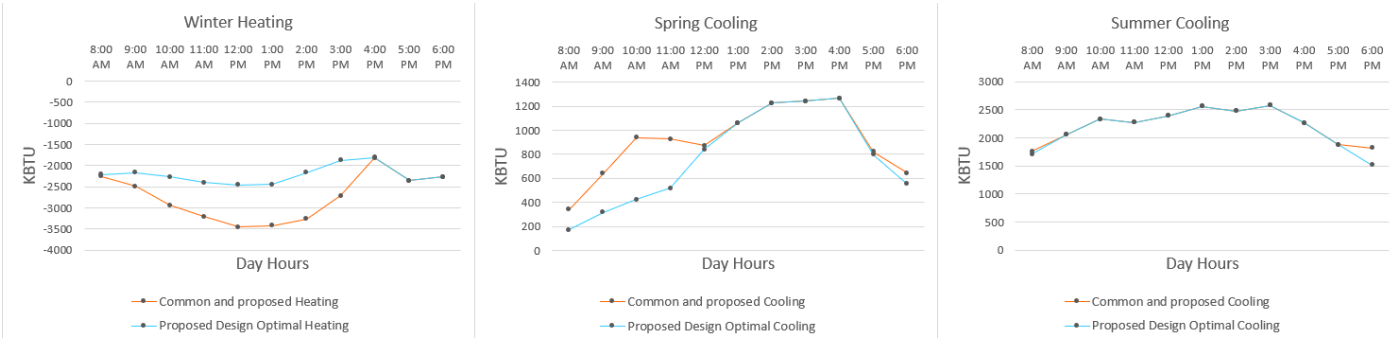


Figure 5. Seasonal cooling and heating loads of one day.

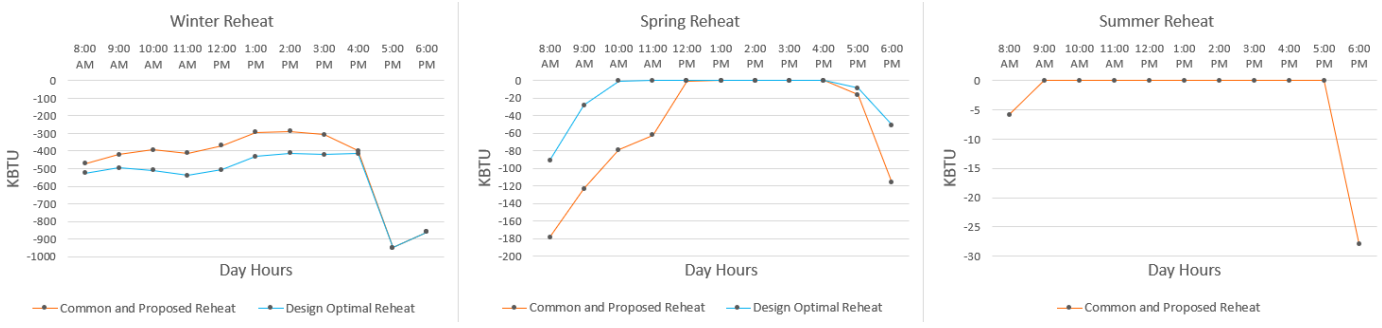


Figure 6. Seasonal Reheat loads of one day.

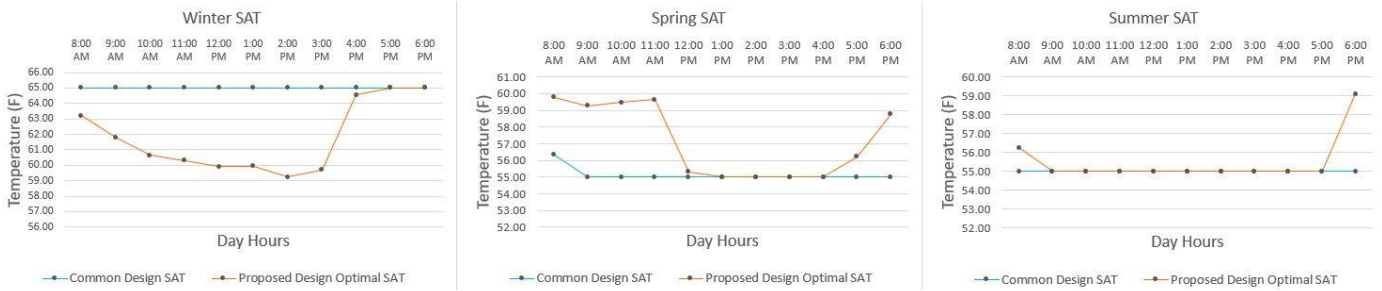


Figure 7. Supply air temperature setpoint (SAT) for one day.

The fan power is another essential factor illustrated in Figure 8 in the same condition for three seasons. As discussed in Section 2.1, the pressure drop is lower due to employing one coil instead of two in the proposed system, and, as a result, less fan power is required.

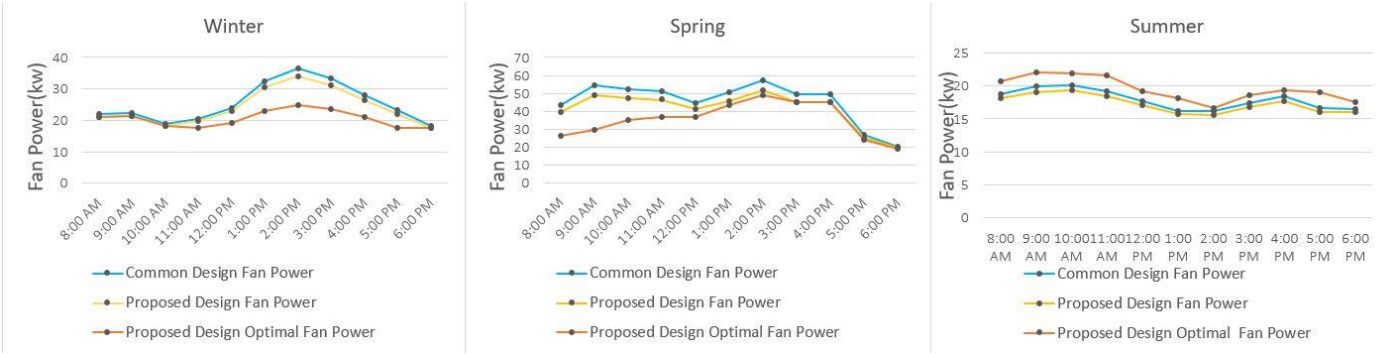


Figure 8. Seasonal Fan Power.

In winter, the proposed design fan power is reduced by 6% and the design optimal by 20%, saving electricity consumption. This trend continued to spring with more savings in fan power, with 9% and 28%, respectively. The last case was countered with a different scenario as fan power increased in the design optimal by 9%. As discussed, in the summer cooling load, the reheat boiler will use a reset supply air temperature strategy (Figure 7), and heat pumps must supply all zones' loads. As a result, the fan power will increase in this condition.

4.2. Annual Electricity and Natural Gas Consumption for the Proposed Configuration

Three cases are simulated to show the proposed configuration's annual electricity and natural gas consumption. All cases and conditions are the same, as discussed in Section 4.1. The three scenarios are then simulated for yearly electricity and natural gas consumption in different USA climate zones to evaluate the proposed configuration's benefits.

It can be observed from Figure 9 that the proposed configuration has significant savings from the common design in cooling-dominated climates even though the air source heat pumps are utilized. In this case, all of the components of the HVAC system consuming electricity, such as the fan, pumps, etc., are considered and added together for total annual electricity consumption. The electricity consumption also accounts for the lower pressure drop through the coils due to employing one coil instead of two in a typical design, leading to fan power reduction. The savings vary from 3.3% to 1.8% in Orlando, Phoenix, Austin, and LA. When mixed and heating-dominated climates are considered, electricity consumption increases for the same reason. The air source heat pumps have significantly lower efficiency in colder climates, leading to higher energy consumption. This can be minimized using a dual-fuel heat pump or shifting supply air heating to local reheats. On the other hand, when an optimal SAT reset is used in scenario 3, the electricity usage decreases significantly for most of the climate zones. The savings vary from 11.8% to 2.0%, even though the heat pumps use electricity as the energy source.

As shown in Figure 10, the proposed configuration offers substantial savings from the typical design when considering natural gas consumption. The air source heat pump serves the system heating load for the proposed configuration resulting in lower gas consumption in all of the climate zones. The only source of natural gas consumption is the boiler for local reheat. Due to this, the savings range from 10.2% to 67.0%, where heating-dominated climates demonstrate more savings. In addition, optimizing the supply of air temperature leads to further savings in natural gas consumption in most climate zones varying from 45.3% to 66.0%. These energy consumption results demonstrate the benefits of the proposed configuration; an optimal supply air temperature reset reduces electricity consumption and provides an efficient way of electrification and decarbonization of 'buildings.

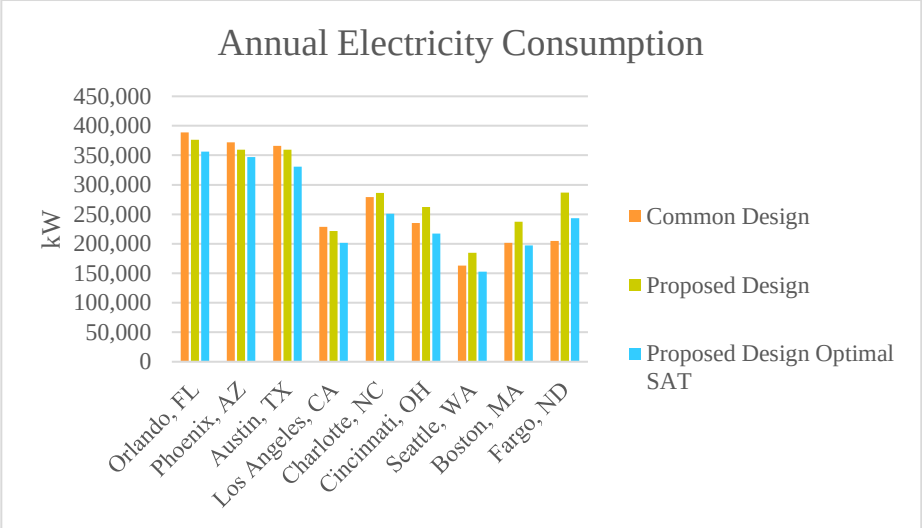
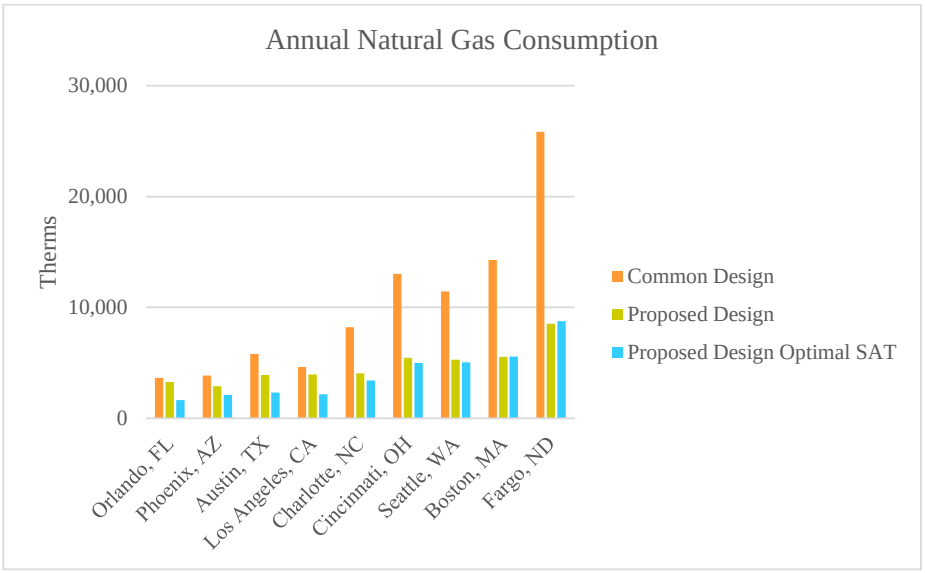


Figure 9. Annual electricity consumption and percentage of savings from conventional design for the proposed configuration.



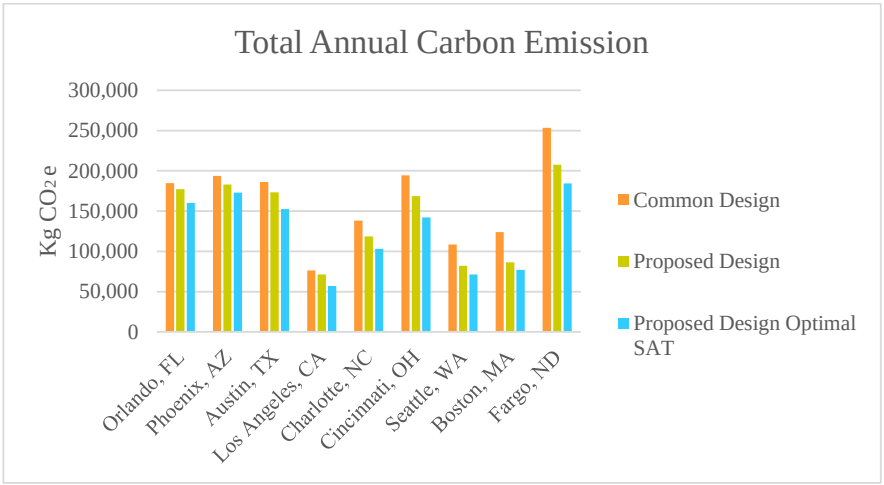
Savings in Percentage	Orlando, FL	Phoenix, AZ	Austin, TX	Los Angeles, CA	Charlotte, NC	Cincinnati, OH	Seattle, WA	Boston, MA	Fargo, ND
Proposed Design	10.2	25.3	32.9	14.5	50.5	58.1	53.8	61.2	67.0
Proposed Design with Optimal SAT	54.8	45.3	60.1	53.1	58.6	61.7	55.9	60.9	66.0

Figure 10. Annual natural gas consumption and percentage of savings from conventional design for the proposed configuration.

4.3. Carbon Emission Reduction for the Proposed Configuration

The carbon emission varies in different cities according to the electricity and natural gas usage coefficient described in the methodology. So, the CO_2 emission for the proposed system is calculated compared to the conventional chilled water VAV system to evaluate the benefits of the proposed configuration. As the proposed configuration uses heat pumps replacing the chillers and one boiler, it reduces the use of natural gas, leading to the electrification of the building. From each case's electricity and natural gas consumption, the CO_2 emission for electricity and natural gas consumption are calculated separately for each

climate zone. The total amount of CO_2 emission in Kg CO_2 e annually is then calculated from those numbers. As can be observed from Figure 11, the amount of CO_2 emission is substantially reduced when the proposed system is considered. The reduction ranges from 4.1 to 30.5%. The mixed climate zones have the most amount of CO_2 emission reduction. Similarly, when the proposed system with optimal supply air temperature is considered, a further reduction can be achieved, corresponding to lower energy consumption for this scenario. Annual CO_2 emissions can be reduced by 10.8 to 38% in different climates with the proposed SAT reset. Overall, it appears more advantageous for energy consumption and CO_2 emission when the optimal supply air temperature (SAT) strategy is adopted with the proposed configuration. This can lead to significant energy and cost savings along with a lower environmental impact in the long run.



Reduction in Percentage	Orlando, FL	Phoenix, AZ	Austin, TX	Los Angeles, CA	Charlotte, NC	Cincinnati, OH	Seattle, WA	Boston, MA	Fargo, ND
Proposed Design	4.1	5.6	6.9	6.7	14.2	13.3	24.3	30.5	18.0
Proposed Design with Optimal SAT	13.3	10.8	18.0	25.1	25.4	27.0	34.1	38.0	27.1

Figure 11. Annual CO_2 emission and reduction in percentage from conventional design for the proposed configuration.

5. Discussion

The building industry consumes the greatest proportion of energy generated, and hence plays a critical role in the depletion of natural resources, the creation of air pollutants, and overall environmental degradation. Building energy-saving techniques can provide several economic and environmental benefits. It is critical to use software that can simulate a building's energy behavior in order to determine the optimal processes that result in energy savings. This study did an energy evaluation of a mid-size office building and identified energy improvement strategies based on proposed new configuration. Following the implementation of the scenarios, the yearly energy consumption for power and fuel, annual energy savings, and annual CO_2 emissions were calculated.

For office building modeling and energy evaluation conventional VAV systems with air -cooled chillers and gas-fired boilers are used. Although these systems can effectively cut total energy use, they cannot eliminate the use of fossil fuels, resulting in increased carbon emissions and significant environmental repercussions. To accomplish electrification and decarbonization of buildings, the proposed common coil layout utilizes air-source heat pumps and an efficient boiler for reheating coil. Unlike the conventional system which employs separate boilers for heating and reheating, the suggested common coil layout has a more efficient boiler for reheating coil. This layout also necessitates less piping and a smaller boiler size, which might result in a more streamlined and cost-effective system for servicing the VAV box reheat coils for local reheat needs.

The study found that this structure can significantly reduce energy consumption and CO_2 emissions in heating-dominated regions. The proposed configuration achieved electrification and decarbonization of buildings and showed savings from the typical design when natural gas consumption is considered. Heat pump and energy reduction supplied 36% less with heating-dominated climates demonstrating higher natural gas savings. In this regard, it is worth noting that, in contrast to Kolokotsa et al. [31], only a 30% decrease in energy consumption was achieved, and Wai's [32] research of energy-saving strategies for a Taiwanese university only resulted in a 16% reduction in yearly energy use. Optimizing the supply air temperature further reduced natural gas consumption in most climate zones by 45.3% to 66.0% and led to annual CO_2 emissions reductions in average of 25% in different climates with the proposed supply air temperature reset which is better than Tsantili [33] result by getting 20% with different scenarios.

The common coil configuration results are limited in that they are based on simulation and a theoretical analysis rather than an experimental study. While the analysis highlighted the potential advantages of the new design, there is no actual evidence to back up the findings. Furthermore, there is no program available that can model the suggested setup and simulate its performance without new programing per new configuration, therefore we were unable to validate the MATLAB results. Without such tools, it may be hard to accurately predict the energy savings and CO_2 emissions reductions that may be obtained in real-world applications.

Overall, the results of this study suggest that the proposed common coil configuration has the potential to significantly reduce energy consumption and CO_2 emissions in buildings, particularly in heating-dominated climates. However, further research is needed to investigate the applicability and cost-effectiveness of this configuration in different types of buildings and usage patterns.

6. Conclusions

In this study, we have investigated the potential use of heat pumps in achieving electrification and decarbonization of buildings for space heating and cooling. Our proposed common coil configuration, which utilizes air-source heat pumps and a boiler for reheating coil, has demonstrated significant savings compared to traditional designs that rely on natural gas consumption. Our results indicate that savings range from 10.2% to 67.0%, with heating-dominated climates showing greater potential for savings. By optimizing the supply air temperature, we were able to achieve further reductions in natural gas consumption in most climate zones, ranging from 45.3% to 66.0%. The proposed system also resulted in a reduction in CO_2 emissions ranging from 4.1 to 30.5%, with even greater reductions achieved when the optimal supply air temperature was employed. Annual CO_2 emissions were reduced by 10.8% to 38% in different climates with the proposed supply air temperature reset. Our findings suggest that using the optimal supply air temperature technique with our proposed common coil configuration is highly beneficial for energy usage and CO_2 emissions reduction. This approach can result in significant long-term energy and cost savings while also reducing the environmental impact of buildings.

Through further research, it is crucial to more investigate the relationship between occupant behavior, energy consumption, and carbon emissions reduction to understand the impact of occupant behavior on energy efficiency. Field studies that gather data on occupant behavior, such as energy usage trends, thermostat settings, and lifestyle preferences, might give useful insights into the elements that influence occupant behavior. These findings may be utilized to create successful tactics that encourage energy-efficient behavior, which can be used in conjunction with retrofitting efforts to increase overall energy efficiency. Furthermore, experimenting with novel techniques, such as individualized energy usage feedback and customized occupant education programs, can improve initiatives aimed at promoting sustainable behavior and lowering carbon emissions in buildings. We hope that our study can inform policymakers, engineers, and building owners about the potential of heat pumps and optimal supply air temperature techniques for sustainable building design

and operation. Further research is needed to explore the practical implementation of these findings and to address any remaining challenges.

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