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Research Article

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HVAC System Design for Building Efficiency in KSA

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Abstract Air conditioning is a complex field that encompasses the simultaneous management of all mechanical parameters essential for the comfort of individuals, animals, and industrial or scientific processes. The system consists of parts and equipment organized to meet different conditions required for comfort in residential and industrial settings. Increasing demand has led to rapid growth in air conditioning systems and manufacturers, with a focus on selecting the right system for energy efficiency. Improving energy efficiency in HVAC systems is crucial due to rising energy consumption over recent decades, which raises concerns about future energy crises and environmental impacts. Measures aimed at improving energy efficiency in buildings are intended not only to reduce energy costs but also to offer additional benefits such as lower maintenance requirements, improved comfort, reduced electricity use for lighting and appliances, and enhanced property value. HVAC systems can be categorized by their method of heating control within conditioned spaces. This analysis guides on selecting suitable systems based on specific application needs while considering short-term and long-term goals. Achieving efficient HVAC systems requires enhancements in integrated mechanical components design as well as optimal plant operation — contributing to significant reductions in power consumption considering that buildings account for over 40% of total power consumption in developed countries. This Special Issue focuses on advancing understanding related to efficient HVAC systems including cooling technologies, component design optimization strategies like regenerative processes, and effective handling of thermal storage aspects.

Keywords HVAC system design, Building efficiency, Energy consumption, Energy savings, Saudi Arabia, Building envelope design, Thermal insulation, Window glazing, Solar shading, Energy performance modeling, Life cycle cost analysis, Energy conservation measures, Energy efficiency strategies, HVAC operation optimization, Sustainability

1. Introduction

The energy efficiency of a building is assessed by comparing its energy consumption per square meter of floor space to established benchmarks for specific types of buildings in particular climatic conditions. These benchmarks, typically measured in kWh/m2/annum, represent the median level of performance and are used to evaluate heating, cooling, lighting, ventilation systems, and electrical instruments. U-Values measure heat loss through materials and specify minimum energy efficiency requirements for windows, doors, walls, and other exterior building elements according to standard↵building codes. Governments must ensure a secure energy supply for economic development across different nations. Increasingly changing climate patterns are affecting hydroelectricity-dependent nations and causing significant power shortages. Investing in energy efficiency within buildings can be more cost-effective compared to expanding the energy system's supply side; it not only reduces utility bills but also minimizes consumed amount while maintaining services provided such as heating & cooling, water heating, lighting/electricity consumption, and comfort levels [1-2]

Developing an energy performance model for a representative industrial building involves selecting a representative building, developing a base-case energy performance model, and verifying and adjusting the model to achieve an acceptable correlation between expected and actual energy consumption. A representative building is selected based on criteria such as potential for energy savings, size and occupancy type, geometrical configuration, floor space, and owner cooperation. The final thermal and physical characteristics of the selected buildings are considered along with the operation schedule, construction strategies, materials used, and annual/monthly energy consumption obtained from utility bills to identify secondary variations. Both quantitative and qualitative analyses should be performed including verification of indoor thermal quality reflected by utility bills to ensure indoor thermal comfort conditions are well understood. Energy performance modeling involves utilizing detailed energy simulation programs that can predict accurate energy performance over time considering factors such as building schedule, occupancy, and mass while offering life cycle cost analysis options. The process begins with an accurate survey followed by inputting structural data, internal loads, schedules, outdoor climatic data, HVAC components, etc., into the simulation engine to formulate an ongoing base model using detailed information about the representative building mentioned previously. Due to modeling limitations, the initial predictions may differ from actual values, hence it becomes necessary to adjust the base model for improved accuracy when implementing different ECMs. Calibration involves closely matching individual systems' performances (modifying thermal loads and schedules within areas on the table range and adjusting consumption parameters based on collected data confidence) summarizing the different techniques adopted and corresponding savings obtained [3-4].

The research focused on studying the impacts of building envelope parameters, HVAC systems design and operational techniques, and system design on energy consumption in selected buildings across different climate zones. The study involved an extensive literature review to assess energy efficiency, thermal comfort conditions, and common practices adopted in residential and commercial buildings. Data was collected from prototypical residential buildings in various cities of Saudi Arabia for energy performance analysis. Energy efficiency measures were explored with a focus on HVAC system design to achieve significant energy savings. The objective was to establish guidelines for improving energy efficiency in commercial and residential buildings across different climate zones of Saudi Arabia.

2. Analysis of energy efficiency options for KSA buildings

A detailed simulation analysis evaluates the impact of energy efficiency measures on existing and new buildings, including effects on energy consumption, peak demand, and carbon emissions. Life cycle cost analysis determines optimal measures for building energy performance enhancement in various climatic conditions in Saudi Arabia. The study focuses on residential buildings and uses a sequential search technique that considers different applications to perform optimization analysis. Results indicate that space cooling is the main contributor to annual electricity consumption for an archetypical KSA villa, with varying impacts across different cities. Heating may be necessary in some regions to maintain indoor thermal comfort.

A prototypical residence in KSA climates is formed to assess optimal building envelope design for residences. According to a survey, about 40% of the residential building stock in major KSA cities is classified as villa type. Energy Plus was selected for whole-building energy simulation analysis, known for its accuracy compared to other methods. A baseline energy model has been developed and used for assessing various energy efficiency options to enhance the design of villas in KSA based on a study performed by KACST. The air-conditioning system specifications and building construction characteristics are summarized in the tables provided.

The monthly energy simulation results for the prototypical villa in Riyadh show that 66% of the total annual electrical energy is consumed by space cooling. Similar simulations were conducted for Jeddah, Dhahran, Tabuk, and Abha showing variations in space cooling and heating energy usage across different KSA cities. For all locations including Riyadh, space cooling remains the dominant contributor to overall annual villa energy consumption.

In the analysis of five KSA sites, space cooling dominated. Enhancing building envelope performance through measures such as thermal insulation, window glazing, and solar shading is important to reduce cooling loads. However, a detailed thermal and economic analysis is necessary to identify the optimal selection of building envelope components. For example, adding significant thermal insulation to exterior walls and roofs may not be effective due to diminishing returns. The effect of wall or roof insulation on annual energy use shows similar patterns for all KSA climates with most energy savings achieved by adding the first R-5 insulation. More savings are observed in hot climates like Riyadh and Jeddah. Adding R-5 wall insulation results in 5.5% energy savings for a villa in Abha and almost 12% in Riyadh. Conversely, Jeddah gets the lowest energy savings from added roof insulation due to lower direct solar radiation levels during the summer months. Window-shading devices' impact on energy use was evaluated across all five KSA sites based on overhang projection length (Fig 1).

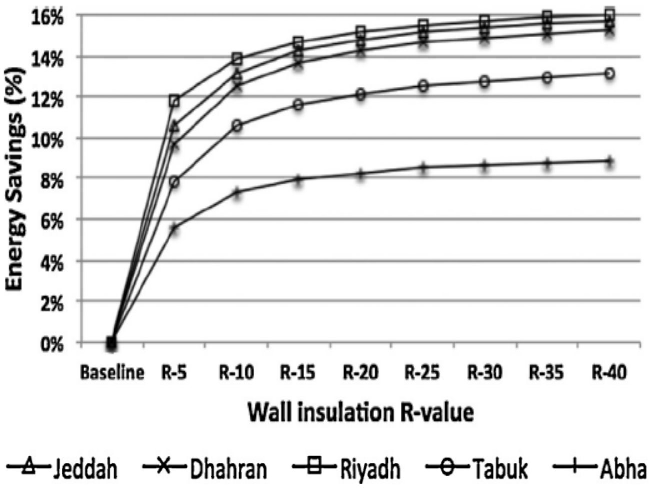

Figure 1: Energy Savings from wall and roof insulation for a villa located in five KSA cities

The lowest energy-saving result from overhang shading was seen for Dhahran compared to other locations because it has less solar radiation leading to fewer heat gains through windows than places like Riyadh.

Optimization analysis is performed to estimate the cost-effectiveness of adding energy efficiency measures to design a villa in different KSA climates. The optimization approach uses a sequential search methodology and considers Photovoltaic solar energy to meet the electrical energy consumption needs. The life cycle cost and energy savings attributed to the PV system are included in the analysis, with results showing significant subsidies provided by the KSA government for lower domestic energy costs. The optimum cost-effective package for the villa in Riyadh can achieve a 39.5% energy savings relative to the base-case villa design configuration with an LCC of $24,173, comprising window shading, roof insulation, wall insulation, and double glazing window as summarized in Table 1.

Table 1. Energy saving measures as percentage and their aspect on the life cycle cost

Energy measure	Cumulative energy savings (%)	LCC($)
Shading overhang (70 cm)	5.4%	34,390
Roof insulation (R-25)	23%	130,922
Wall insulation (R-15)	36.5%	26,595
Glazing (double air)	39.5%	24,173

Residential air conditioning in Saudi Arabia involves concrete structures with cement brick walls, ceilings ranging from 3 to 3.3 m high, and windows made of thin clear, or tinted commercial glass. Most houses have dedicated guest rooms on the ground floor and bedrooms on the first floor. Due to high temperatures and humidity, all living spaces need air-conditioning, with window units being more common than central systems due to cost considerations. Energy consumption is directly proportional to ambient temperature and efforts are being made by local authorities to promote energy efficiency in new construction projects. Data collected for about 200,000 housing units shows that energy consumption during the cooling season is higher in Dammam compared to Al-Hassa and the Northern area due to its extremely dry climate influenced by Gulf waters. Power consumption is also affected by relative humidity and solar radiation according to an analysis performed using a specific model represented as Ep= E (T, R, S).

3. A Case Study for Three floors Educational Building in Saudi Arabia

Calculating the thermal load of a building is crucial for selecting the right A/C equipment and air handling unit to ensure optimal operation and proper air distribution in the conditioned space. Factors considered include the highest summer temperature, lowest winter temperature, location, construction materials, heat transfer equations, wall types, roof structures' impact on cooling loads, and orientation-based heating/cooling evaluations. Additionally evaluating weather data at different orientations can also be beneficial. The city of Rabigh in Saudi Arabia is located at approximately 39° E longitude and 22.48° N latitude within the Makka Al Mukarrama zone with a population of about 35,000 (Fig 2).

Figure 2: General Location of Rabigh

The building measures 30*30*16 m with three floors constructed using steel beams (30*30 cm), and black concrete blocks (20*20*40) with polystyrene insulation surrounded by granite tiles. The roof consists of a concrete slab above metal sheets with water insulation underneath followed by thermal insulation materials. Air conditioning loads involve cooling the air in summer while heating it in winter; the room's cooling load comes from internal/external sources that need removal to maintain comfortable temperatures. Calculating thermal load requires factors such as areas of envelopes/glass, U-factors, temperature difference between inside/outside, glass transmission factors/lighting density/motors/personnel activities present indoor/outdoor air enthalpy/conduction/convection/radiation through external walls/windows/building usage/local annual weather data/computer simulation programs like HAP or simpler methods using CLTD, SCL, and CLF method developed by ASHRAE based on building material/color/location [5][4].

Thermal loads in buildings are influenced by factors such as heat transfer through windows, infiltration due to gaps in windows and doors, ventilation for fresh air, heat gain from infiltration and ventilation outside air, sun transmission through glass, electric power flow into lamps causing heating up of components, equipment that produces heat within the space, people occupying the space generating sensible and latent heat. Heat calculations were performed for a small portion of the building using specific equations. The suitable air-conditioning system can be selected based on capacity requirements, initial running costs., required system reliability flexibility maintainability architectural constraints indoor air quality. Direct expansion systems are suitable for smaller or medium-sized buildings free of multiple thermal zones while central HVAC systems can be efficient and lower cost for larger setups requiring 100TR or more. Considerations when deciding on an A/C system include stability of the thermal load and accumulation of a large number of people at one place during certain times.[3] The building has three main floors with distinct needs for air cooling systems. The ground floor, used for labs and experiments, requires separate split units due to the need for good ventilation and specific control. Meanwhile, the 1st and 2nd floors can be served by a central system (package units) along with corridors to ensure comfort zones and thermal response. Energy analysis is performed considering wet bulb effectiveness and dew point effectiveness essential in evaluating air cooling systems' performance.

Figures showing wet bulb and dew point effectiveness are presented.

Thermal load analysis was conducted for an educational building located in a hot and humid area in Saudi Arabia. The HAP program, developed by Carrier was utilized to estimate the cooling load. Based on the analysis, appropriate air-conditioning systems were chosen for the building. An energy analysis was carried out to assess the system's efficiency, revealing strong performance.

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4. Applying Energy Efficiency Measures To The Building Under Study

According to the evaluation of the energy use pattern of the building, various energy conservation measures were analyzed and divided into three categories: Level 1 (no cost), Level 2 (low cost), and Level 3 (major investment). Level 1 measures are those that can be implemented through operational and behavioral changes without requiring system or building alterations, thus incurring no extra costs. An example is adjusting the set point temperature. The cooling temperature was set at 25 °C for summer and at 22 °C for winter compared to the base case set point temperatures of 24 °C for summer and 20 °C for winter. It resulted in a 3% annual reduction in energy consumption when tested at different temperatures using the Visual DOE 4.0 simulation program.

The indoor air temperature is adjusted during unoccupied nighttime to reduce energy consumption from 11:00 at night until 7 a.m. the next morning, with temperatures set at 28°C for summer and 16°C for winter. This results in an average of 5% energy savings, particularly in the summer months (Fig 3).

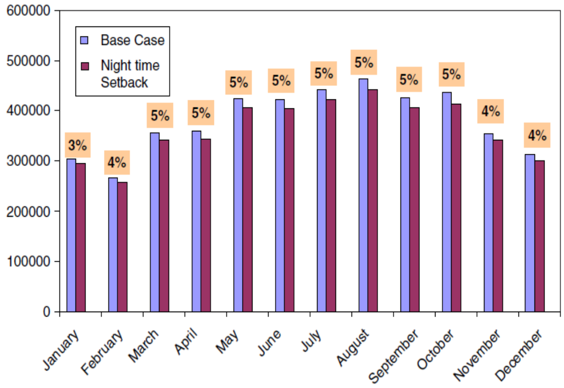

Figure 3: Monthly energy savings results from applying nighttime setback mechanism

Scheduling the operation of building lighting and equipment is often overlooked but remains an important energy conservation measure in many facilities. In the analyzed building, lighting and equipment were initially used continuously during unoccupied and low occupancy hours. However, after adjustments were made to turn off some lighting and equipment during these periods, monthly electric energy savings of up to 5% were achieved as shown in Fig 4.

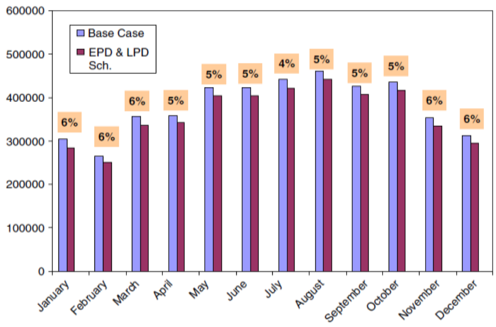

Figure 4: Monthly energy savings results from applying schedule of lighting and equipment

Two types of thermostats, "Two-position Type" and "Reverse Action Type," were assessed for energy savings. The simulation showed that the "Two-position Type" thermostat saved almost 0.13% in energy consumption compared to the base case, while the "Reverse Action Type" increased energy consumption by 0.1% due to increased airflow with a higher cooling load.

Based on the study of the building, 50mm thick polystyrene insulation is used in walls with a U-value of 0.46W/m2C. Increasing the insulation thickness can lead to an average electric energy savings of around 16%, making it a cost-effective and essential measure for conserving energy.

Energy-efficient windows (high R-value and low emissivity) can decrease energy use and improve indoor comfort levels. The existing double-glazed window with a U-value of 3.5W/m2C7 was replaced with a low-emittance double-glazed window, resulting in an average 7% reduction in energy consumption. These savings are attributed to the large area of glass in the building and the impact of the glazing system on energy use patterns and internal heat gains.

Lighting in office buildings typically accounts for 40% of total electrical energy use. Several affordable measures can improve lighting efficiency, such as using energy-efficient lamps and ballasts, as well as reflective devices. In the case of the building being studied, 40W fluorescent lamps are currently in use. The implementation of an energy conservation measure resulted in an average monthly electric energy savings of 4.5%.

The implementation of these measures requires significant financial investment and can be carried out through system renovation or retrofitting in existing office buildings, as well as for new projects. One specific measure involves replacing the constant air volume system with a variable air volume system. In the CAV system, all AHU fans operate at a constant speed and supply conditioned air using a constant volume of air supply to the conditioned areas [2, 6]. This design is intended to provide sufficient cooling for the building but results in higher energy consumption. By transitioning to a VAV system, which adjusts the amount of supplied air based on zone load, less energy will be required to condition different zones resulting in approximately 17% reduction in energy consumption overall due to the inclusion of variable speed drive fans.

Applying an enthalpy economizer with the VAV system and CAV-Rh system would increase energy savings by 3% for both systems compared to the base case. The use of an enthalpy economizer with the VAV system generated significant energy savings (25.5%) even when operating at low temperatures (T = 20°C). This strategy was followed by replacing the unitary system with VAV and TPFC systems, resulting in almost 22% energy savings under base-case conditions.

Implementation challenges and obstacles to energy efficiency programs, including social, economic, legal, and institutional aspects are significant. It is recommended that governments enforce policies to ensure the success of wide-scale energy efficiency programs in residential buildings. Energy refurbishments can lead to substantial improvements in an economy's energy efficiency and contribute to sustainability objectives. However, real-world constraints such as local market conditions and financial barriers need to be considered for cost-effective investments [7-8].

The cost of building energy retrofit depends on factors such as building size and physical conditions. Energy savings can result from enhancing building components in KSA, benefiting both owners and the government. Financial benefits to the KSA government are discussed to highlight reasonable policies for improving energy efficiency in residential buildings. Analyzing the study's results, Fig 4.10 presents estimates of energy cost potential and payback after investments. A level-1 retrofit is identified as the most cost-effective option, offering enough savings to prevent additional investment in power plants.

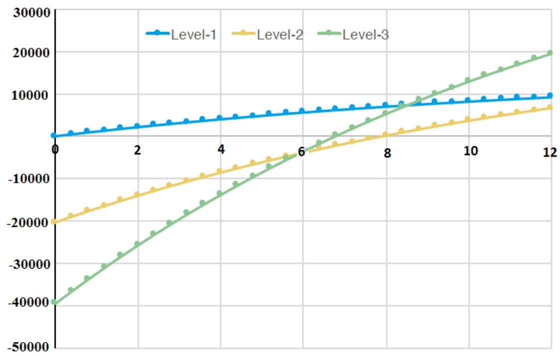

Figure 5: Payback period of investment options in residential building educational building under study

The efficient functioning of the heating, ventilation, and air-conditioning system is vital for optimizing a building's energy consumption, reducing costs, enhancing occupant comfort, and ensuring environmental quality. Several strategies related to HVAC operation aimed at conserving energy were implemented and their impact on energy usage and thermal comfort was assessed. Table 2 presents the identified strategies for evaluating buildings in Saudi Arabia. It is recommended to prioritize measures that do not require investment as they yield immediate returns in terms of energy savings. As for necessary investments, budget allocation is essential before proceeding with any implementation.

Table 2: Estimated energy savings and mean investment cost of energy efficiency measures

EE measure	Energy savings (%)	Options	Cost ($)	Total ($)
Set point temperature	3%	25 °C for summer and at 22 °C for winter	-	-
Nighttime setback	5%	28°C for summer and at 16 °C between 11pm and 7am	-	-
Schedule of lighting and equipment	6%	turning off some lighting and equipment's during unoccupied	-	-
Insulated wall	16%	polystyrene	8.56 $/m^2$	20000$
Insulated roof	15%	polystyrene layer	16 $/m^2$	30000$
Glazing system	7%	low-emittance double-glazed window	102 $/m^2$	22000$
Energy efficient lamps	4.50%	40W fluorescent lamps are used	4$/unit	4000$
Replacement of air-cond system	17%	VAV system	10000$	19000$

5. Conclusion

Improving energy conservation in HVAC systems: implementing a VAV or TPFC system instead of the unitary system can save up to 22% of energy, while a 28°C set point temperature during unoccupied periods results in an additional 18% saving. Adding an enthalpy economizer can contribute up to 3% more savings. Overall, it is possible to achieve essential energy savings of about 25% through various HVAC operation strategies. Optimizing building envelope systems for residential buildings in Saudi Arabia involves analyzing wall insulation, roof insulation, thermal mass associated with exterior walls, window shading, and glazing type across different climate zones. Recommendations include employing nighttime setbacks and adjusting lighting and equipment schedules for unoccupied hours to reduce electricity consumption. It is recommended to use low-emittance double-glazed windows for energy efficiency in large-glazed buildings in hot climates. Energy-efficient lamps of fluorescent type with a power of 34W or less are also recommended and can be used in existing buildings when the current lamps burn out. Air-conditioning systems play a major role in energy consumption, especially during extreme weather changes; it is strongly recommended that VAV systems be used for system renovation and considered for future office buildings.

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