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Optimizing Indoor Air Quality and Energy Efficiency in Hot-Dry Climates: A Calibrated Simulation Study of HRV/ERV Performance in Baghdad

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Abstract

Maintaining indoor air quality while limiting cooling energy demand is challenging in hot, dry climates. This study compared heat recovery ventilation (HRV) and energy recovery ventilation (ERV) combined with air conditioning (AC) or direct evaporative cooling (EC) for a single-zone residential space in Baghdad. An EnergyPlus model evaluated four configurations under Baghdad weather conditions, considering electricity consumption, thermal comfort, humidity control, and water use. ERV with AC reduced electricity consumption by approximately 8.3% compared with HRV with AC. EC configurations reduced electricity consumption by more than 80% relative to the corresponding AC configurations, but required additional water. Within the EC configurations, ERV showed slightly lower electricity and water consumption and better humidity control than HRV. AC configurations maintained more consistent thermal comfort, whereas EC configurations approached or exceeded upper comfort limits during peak summer conditions. These findings indicate an energy–water trade-off in selecting ventilation and cooling systems. Under the simulated conditions, ERV offered advantages in electricity consumption and humidity control, while the suitability of evaporative cooling depended on water availability and thermal comfort requirements.

Keywords: EnergyPlus simulation; Heat recovery ventilator (HRV); Energy recovery ventilator (ERV); Hot-dry climate; Direct evaporative cooling.

1. Introduction

Energy consumption in the global building sector accounts for about one-third of total energy consumption and one-third of CO₂ emissions from human activity. Over the past few decades, improving indoor environmental quality (IEQ) in addition to reducing energy consumption has become an increasingly important objective. Properly functioning mechanical ventilation systems are critical to maintaining occupant health as well as overall comfort; however, mechanically ventilating with untreated outside air can create significant thermal loads on heating, ventilation, and air conditioning (HVAC) systems. Since this is particularly problematic in extreme climate conditions due to the high cost of conditioning ventilation air, the tradeoffs associated with the design of such systems may be even more difficult to manage.[1]

In the hot, arid climate in which much of Iraq is located, residential buildings face particularly severe challenges from very high temperatures and radiant heat fluxes, as well as frequent dust storms. Summer daytime ambient temperatures in Baghdad can reach 45-48°C, while relative humidity is usually about 20%. The "orange dust" storms not only affect the outdoor air quality but also cause a deterioration of the indoor air quality through these airborne dust particles; by the same token, filtration [2]. Therefore, ordinary split-type air conditioning systems must work almost continuously, and their electrical energy consumption will certainly be very high. [3] Around 80% of all electricity is consumed by buildings [4], and during summer peak periods, the grid is overstrained, with power availability as low as 12 hours per day. Buildings are becoming highly sealed. This raises the need for effective ventilation and cooling strategies offering healthy indoor air while not increasing energy loads.

One promising option is to use balanced mechanical ventilation with heat or energy recovery. Energy recovery ventilators (ERV) and heat recovery ventilators (HRV) exchange heat between the outgoing and incoming airstreams to temper ventilation air [5]. A two-fan, one-exhaust, one-supply balanced system maintains indoor pressure neutrality, enabling filtration on both streams [6]. HRV/ERV units recover energy and provide virtually all the necessary outdoor-air volume at a more favorable temperature and humidity, reducing the heating or cooling load. An HRV core transfers only sensible heat (temperature) while leaving the indoor and outdoor moisture contents essentially unchanged. Transfer of both sensible heat and latent heat (moisture) is carried out by ERV via an enthalpy membrane or wheel [7]. An ERV might, therefore, impose moisture loads while also adding some moisture in a dry area. These differences are important in hot-dry climates: an HRV will supply very dry, cool air for further evaporative cooling [8], whereas an ERV will moderate humidity, which may interfere with thermally driven desiccant cooling stages.

Theoretical advantages of ventilation heat recovery are well documented [9]; however, relatively little has been published about the use of Heat Recovery Ventilation (HRV) and Energy Recovery Ventilation (ERV) systems within the Middle East. An example of a recent Iraqi publication discussed the possibility of combining an HRV with a direct evaporative cooler to precondition supply air before entering the building envelope; however, no analysis was conducted on ERV performance in such climates [10]. Few studies have compared HRV and ERV using climate-specific, simulation-based methods to evaluate the performance of each system type for the extreme summer conditions found in Baghdad. The current knowledge gap will be filled by a comprehensive energy simulation of a typical residential zone (a single room) with weather conditions of Baghdad to compare the performance of HRV versus ERV when used with split air conditioning and with evaporative cooling. This study will systematically assess the configuration options for ventilation and cooling systems to recommend systems that provide maximum indoor air quality at minimum energy consumption in hot-dry climates.

2. Problem statement

Baghdad suffers from a hot summer, which requires cooling homes. As the outdoor air temperature is mostly over 45 °C, it is only possible through intensive cooling to get comfortable. Building ventilation is required to keep locations healthy and comfortable [11], so even insulated, sealed homes must ventilate to the outside at least once per hour. This brings extremely warm air into the cooling load. Most houses in Iraq were supplied with split air-conditioning units, which were never designed for a high ventilation rate [12]. To ventilate the room, if windows are opened or exhaust fans are used from time to time, then the efficiency of the AC unit will drop, and energy usage will rise steeply, as that unit will have to remove from the space not just heat but also the moisture present in the warm air that has entered [13].

Thus, the conventional ventilation strategies have major limitations in this case. When energy recovery is not employed, ventilation of a cooled space makes the AC treat outdoor air that may be 20-30°C warmer than the desired indoor setpoint [14]. These conditions raised peak cooling loads, even for high-efficiency coils. In addition, dust and pollutants from ventilation must be filtered, which increases pressure drop and fan energy [15]. A direct evaporative cooler is also added for economy, but that complicates the problem by raising humidity. Evaporative cooling lowers indoor temperatures [16] but also increases indoor RH. This adds to the moisture load a split-system AC can handle. Either a split system AC could handle it, or the air isn't being flushed, which could result in mould.

Notably, there is little guidance on whether ERVs or HRVs are more suitable for such hot-dry climates [17]. In principle, an ERV would reclaim moisture from the exhaust air and deliver slightly more humid air than an HRV, potentially reducing any need for space humidification in a very dry climate. However, adding moisture to an already-dry climate may not be beneficial if it simply increases latent cooling demand. Furthermore, ERVs and evaporative coolers both introduce moisture streams in the space, raising concerns about indoor humidity control [18]. No published simulation study has yet examined the suitability of ERV versus HRV in a Baghdad-like environment, particularly when these are combined with typical split cooling and/or evaporative pre-cooling. This uncertainty – about the relative energy and IAQ impacts of HRV and ERV systems in Iraqi homes – motivates the current research.

3. Literature review

Research on heat recovery ventilation for energy savings in residential and small commercial buildings has occurred largely in cold and temperate climates [19]. A NIST Net-Zero test house in the U.S. showed that continuous HRV year-round could reduce annual heat pump energy consumption by about 7% compared to unconditioned ventilation [20]. According to the study, the utilization of HRVs during winter caused heating costs to drop by around 36%, although this implementation caused an increase in cooling energy (by ~5%) during the mild summer months [21]. As one might expect, the net benefit of an HRV is highly context-specific with respect to climate and the system. In humid subtropical climates, researchers have reported that ERVs tend to outperform HRVs because they reduce latent loads. A modeling study found that in Miami and Houston, ERVs could reduce total HVAC energy by 10–17% as compared to HRVs [22]. On the contrary, during dry or cool weather, one can notice fewer benefits from ERVs, even compared to a simple HRV, which can help maintain moisture.

Energy penalties result from ventilation in hot, dry areas. The introduction of outside air at 45° C adds a large sensible load, and any moisture exchange can only increase the cooling demand. Many researchers have studied these sanctions and recovery solutions [23]. Solutions based on heat or energy recovery methods can be proposed to reduce the extra load. In regions where it is hot and dry, the addition of evaporative pre-cooling is a very logical complement to ventilative cooling. Although outdoor air temperature can be decreased by direct evaporative coolers to around 10-15°C (or more), they significantly increase relative humidity [24]. Crucially, without additional cooling, direct evaporative cooling is usually unable to meet comfort in very hot climates (e.g., 45 °C and higher). Additionally, continuous evaporative cooling will saturate indoor humidity unless balanced with major exhaust air [25]. Due to this reason, some researchers have investigated hybrid systems: for example, pre-cooling the inlet air with an evaporative stage and then using sensible cooling (or vice versa) gives better efficiency. The reports show great energy savings while indicating that humidity control difficulties are increasingly more difficult.

Overall, there are limited reports in the region on enhanced ventilation techniques. A recent study by Al-Naseri [10] proposed a model of a residential building in Iraq employing hybrid rooftop ventilation (HRV) and a direct evaporative cooling unit. According to the authors, the HRV unit being non-transfer moisture, it supplies very dry, cool air into the evaporative cooling unit, which is favorable for evaporative cooling units. According to the energy modeling undertaken by the authors with the help of the simulation tool IESVE, significant energy savings may be attained by using HRV/evaporative cooling combinations that may result in cooling load reductions of up to approximately 66%, depending upon the size of the components (HRV and evaporative components). The study only considered HRV configurations and did not have the option for ERV configurations. Moreover, the authors used a more expansive multi-room floor layout. They did not report IAQ metrics and indoor humidity trajectory data. As a result, there are knowledge gaps regarding how an ERV would function under Iraqi conditions, whether integrated into a split AC or evaporative cooler, and how each strategy would impact indoor moisture and air quality in a simple single-zone system.

It has been shown in the literature that energy savings can be obtained through heat recovery from ventilation; sensible-to-latent recovery requires a case-by-case evaluation depending on the climate. Thus, there is a strong justification for simulating and comparing the systems HRV and ERV alternatives under hot-dry conditions in Baghdad. A local study, which is calibrated, would enable determination of whether the extra complexity associated with latent heat exchange in an ERV would be an advantage over an HRV under those conditions. The study aims to bridge the knowledge gap by modeling these two types of cooling devices, along with conventional cooling devices, to analyze their indoor temperatures, humidity, and ventilation efficiency.

4. Objectives

The purpose of this study is to investigate and compare HRV and ERV ventilation systems serving a single zone in a residential-scale building in a hot, dry climate similar to that of Baghdad. The objectives are to measure and report the effects the two systems have on indoor air and the cooling energy they require when used in conjunction with either an electric split air conditioner or a direct evaporative cooler. Additionally, the effect of latent and sensible heat transfer on the thermal and humidity performance of each system will be another subject of study. Based on the findings of this study, we can

learn how the ventilation device interacts with an electric AC or an evaporative cooler, as well as with the space. Overall, the long-term objective of this research is to provide evidence to support which ventilation system (ERV or HRV) is most energy efficient while still providing the desired level of occupant comfort in a hot/dry climate. Additionally, we hope to develop recommendations for optimizing hybrid systems (ventilation + evaporative cooling).

5. Methodology

Four main scenarios are defined as shown in Figure 1, each isolating the effect of the ventilation strategy under a given cooling mode:

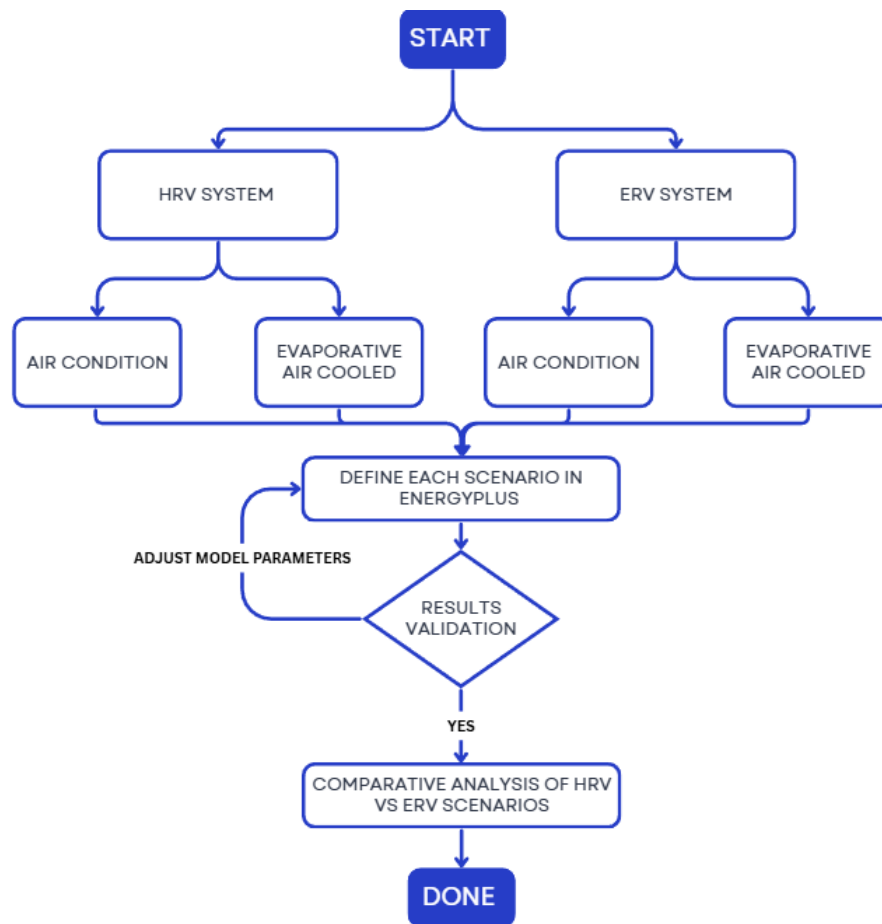


Figure 1: shows the study flow chart.

- Scenario 1 – HRV with Split AC: The space is ventilated by the HRV, which delivers outdoor air. A standard split AC unit provides all cooling. In this scenario, the HRV pre-cools (and dehumidifies by dilution) the air supply by recovering sensible heat, so the AC has a reduced load on the ventilation airstream. This serves as the reference “HRV baseline” case.
- Scenario 2 – ERV with Split AC: This scenario is similar to Scenario 1, but the ventilator is an ERV. This device also transfers moisture, so the air supply comes in at nearly the same humidity

ratio as the exhaust. The AC then cools and dehumidifies this air. Comparing Scenario 2 to Scenario 1 shows the impact of latent recovery: energy use differences will arise from how indoor humidity is retained or shed.

- Scenario 3 -HRV & Direct Evaporative Cooling: In this case, the HRV delivers fresh air, and most of the cooling comes from a direct evaporative cooler. Since the HRV delivers a lower-humidity dry air that will allow more moisture absorption by the evaporative cooler, the evaporative cooler works better than if it were simply receiving ambient air (as would be the case in a non-ventilated cooling application). As in the previous two scenarios, the split AC is turned off here as well; thus, the entire application relies on both ventilation and evaporative cooling. The amount of unmet load (should the evaporative cooler fail to cool to 25° C) should also be documented. This application shows just how much comfort can be achieved using a combination of HRV and evaporative cooling with very little energy.
- Scenario 4 –ERV & Direct Evaporative Cooling: In this case, the ERV provides fresh air to the evaporative cooler. The ERV introduces some moisture into the air through partial moisture exchange, and the evaporative cooler then increases the air's moisture content while cooling it. The increased moisture introduced by the ERV affects the evaporative cooler's ability to cool the space. This represents the interaction between the latent heat gained through the ERV and that gained through the evaporative cooler. It allows us to assess whether the additional moisture has a negative impact on comfort or if additional cooling is required.

Each of these four applications is evaluated over an entire year with the Baghdad weather file to isolate the impact of the ventilation system since all other factors (building envelope, building schedules, and internal loads) are held constant throughout the simulation. When evaluating the results of each application, we can determine what differences are due to the selection of either an HRV or an ERV and what differences are due to the selected cooling system.

5.1 Simulation tool

EnergyPlus (the Department of Energy's whole-building simulation engine) is used for all dynamic modeling [26]. This software allows a detailed representation of building thermal behavior, HVAC components, and air-side equipment [27]. Our EnergyPlus model couples the zone thermal mass, envelope properties, and specified internal loads to HVAC system models for the split air conditioner, evaporative cooler, and HRV/ERV heat exchangers. By running annual simulations using typical meteorological data, we obtain energy-use and indoor-condition profiles at hourly resolution [28].

5.2 Building geometry

The prototypical space is a single-zone residential room with a 4 m × 5 m floor area and a 3 m ceiling height. This yields a volume of 60 m³, which is representative of a small living room or bedroom, as shown in Figure 2. The room has one door (0.9 m × 2.0 m) and one window (1.0 m × 0.8 m). The window is assumed to be double-glazed. To analyze the impact of mechanical ventilation in tightly sealed buildings, the building envelope is treated as an ideal, air-tight building. For a high-performance envelope, Al-Naseri et al. assumed an infiltration rate of approximately 0.6 ACH [10]. Our model effectively minimises infiltration so that outdoor air exchange occurs nearly entirely through the ventilator. All opaque surfaces are assigned thermal properties typical of modestly insulated

construction. Internal heat gains from lights and occupants are set to typical schedules, and any appliances or plug loads are included as constant gains. This setup isolates the cooling and ventilation systems' influence on indoor conditions.

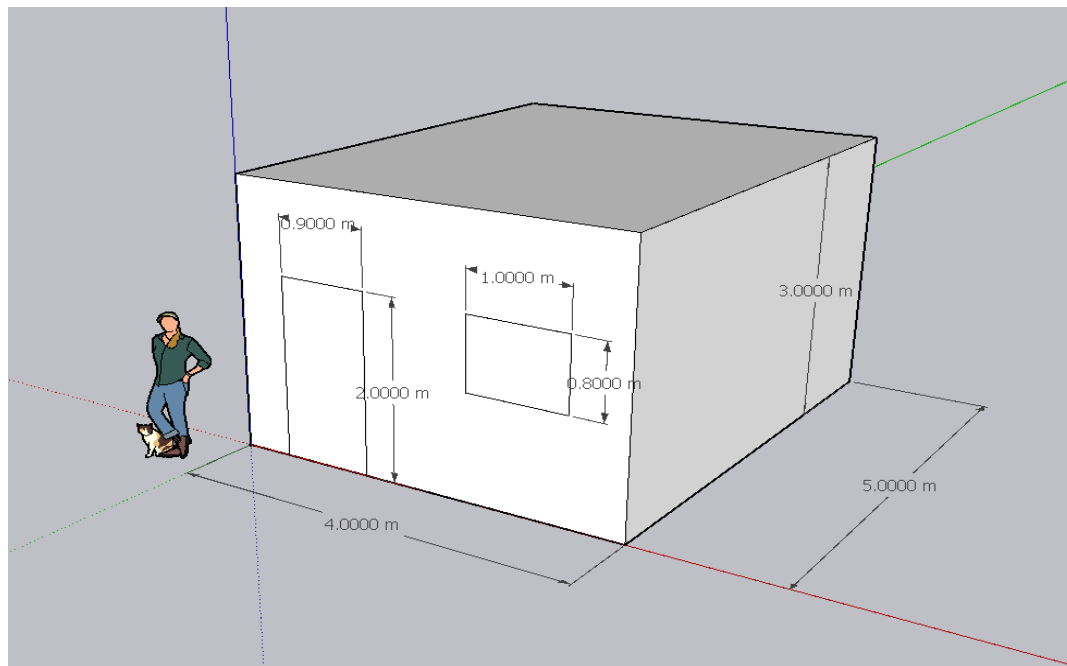


Figure 2: shows the single-zone residential room.

The building envelope was modeled using construction sets representative of Iraqi climatic conditions, as indicated in Table 1, where high solar radiation and elevated ambient temperatures control the thermal performance. High thermal mass and high levels of insulation were included in wall and roof assemblies to reduce heat transfer and peak cooling loads. The glazing properties of the window panels were selected to minimise solar heat gain. By imposing the envelope's effects, these assumptions approximate the impacts of local construction and environment on the room thermal behaviour.

Table 1: shows the construction sets used.

Element	Material/Construction	U-Value $\left(\frac{W}{m^2} \cdot K\right)$
External Walls	Double brick with 50 mm insulation or AAC blocks.	0.40 – 0.60
Roof	Concrete slab with 100 mm thermal insulation and waterproofing	0.35 – 0.50
Windows	Double glazing (6 mm glass / 12 mm air / 6 mm glass).	2.4 – 2.8

5.3 Theoretical background and heat mass transfer mechanisms in EnergyPlus

In hot and dry weather conditions, the operational efficiency of ventilation and cooling systems is highly influenced by the processes related to the transfer of sensible and latent heat. Outside air brought into mechanically ventilated rooms can contribute additional thermal loads to the cooling system. The two loads are the sensible part and the latent part of the load. They will vary depending on the ventilation system and also due to other influences of weather. The total cooling load can be expressed as the sum of sensible and latent components [29]. The sensible cooling load is associated with temperature differences between incoming and indoor air and is defined by:

$$Q_s = \dot{m}c_p(T_{in} - T_{out}) \quad (1)$$

where Q_s is the mass flow rate of air, $\dot{m}c_p$ is the specific heat capacity of air, and T_{in} and T_{out} represent indoor and supply air temperatures, respectively. The latent cooling load is related to moisture removal and is given by:

$$Q_l = \dot{m}h_{fg}(W_{in} - W_{out}) \quad (2)$$

where $\dot{m}h_{fg}$ refers to the latent heat of vaporization, and W is the humidity ratio. In hot-dry climates, such as Baghdad's, sensible loads dominate due to high outdoor temperatures, and latent loads do so due to internal moisture generation and system interactions. HRV (Heat Recovery Ventilation) systems only transfer sensible heat between the exhaust and intake air streams. ERV (Energy Recovery Ventilation) systems transfer sensible and latent energy through an enthalpy exchange process. The effectiveness of sensible heat recovery can be defined as:

$$\varepsilon_s = \frac{T_{out} - T_{in}}{T_{exh} - T_{in}} \quad (3)$$

where T_{exh} is the exhaust air temperature. For ERV systems, latent effectiveness is also considered:

$$\varepsilon_l = \frac{W_{out} - W_{in}}{W_{exh} - W_{in}} \quad (4)$$

These mechanisms impact indoor conditions in different ways. In dry climates, HRV systems are more likely to supply drier air, which can improve evaporative cooling. On the other hand, ERV systems reduce the indoor humidity by transferring moisture from the exhaust air to the incoming air stream. Such systems may dampen indoor humidity swings but may increase latent cooling demand under certain conditions. The mass flow rate of ventilation air is equal to the volumetric flow rate by:

$$\dot{m} = \rho \dot{V} \quad (5)$$

where ρ is air density and $\dot{V}$ is volumetric airflow rate. Higher rates of air supply through ventilation give better indoor air quality but also cause higher cooling loads at extreme outdoor conditions. Direct evaporative cooling lowers the temperature of air by evaporating water in it. Evaporative cooling effectiveness is defined as:

$$\eta = \frac{T_{db,in} - T_{db,out}}{T_{db,in} - T_{wb,in}} \quad (6)$$

where T_{db} and T_{wb} represent dry-bulb and wet-bulb temperatures, respectively. When the temperature of the air is lowered, the humidity increases, thus creating a trade-off between comfort and humidity in this process. The interplay between temperature drop and moisture extraction determines the overall efficiency of ventilation and cooling systems. When the supply air humidity is reduced, the effectiveness of evaporative cooling in HRV-assisted systems is enhanced. This is because the air will be able to absorb more moisture. On the other hand, ERV systems can recover moisture from exhaust air, which helps maintain stable indoor relative humidity. Consequently, the air can no longer be effectively cooled

through evaporative cooling. An air-conditioning system benefits from the ERV, which reduces sensible and latent loads by heat exchange. Energy consumed for overall cooling will be reduced. There is higher water consumption to reduce electrical energy usage in evaporative cooling systems. This agreement governs its performance. The heat and mass balance principles that are discussed in EnergyPlus are the basis for the Numerical Simulations. The computer program will solve the equations of transient energy and moisture balance for the building and HVAC systems to allow the detailed analysis of the interactions between ventilation strategies, cooling techniques, and indoor environment conditions.

6. Results

A model of a typical residential room in Iraq is simulated in EnergyPlus. The room model is 20 m² (length x width = 4 m x 5 m). The room model assumes conditions that reflect local building practice, local climate conditions, and thermal comfort studies of a hot, dry climate. Assumed to be a typical residential building that conforms to internal heat gains and occupancy. The 1-2-person occupancy of the space is considered typical for single-room residential use. The activity level is similar to seated, light work and produces around 120 W each of sensible and latent heat. The internal gains from lighting and plug load were modeled as a total load of about 150–200 W, consisting of LED lighting and common household electronics.

The cooling set point and system operational time frame were chosen to correspond to an extended period of cooling demand that one could expect to experience in summer conditions in Iraq, with outside air temperatures frequently exceeding 45 °C. The indoor cooling set point was maintained at 24 – 26 °C during occupied periods and was intended to provide thermal comfort in line with regional comfort expectations and international norms. To achieve peak solar gains and late-night occupancy, the cooling system was supposed to operate for about 10–14 hours/day during the cooling season (midday until late night; 12:00 p.m. until 2:00 a.m.). In all, the cooling system would operate for about 2800–3200 hours per year (April to October).

A Schedule: A compact object in EnergyPlus was used for time-dependent schedules. With a fractional schedule, the occupancy was modeled, where the highest value (up to 1.0) represents the occupation in the evening and nighttime, and a lower value (0.2 – 0.3) is the daytime occupation, as this is the time period when it is assumed that the occupants are out of the house at work or school. The set-point cooling schedule was defined as a constant temperature during system operation (when the system is ON) and a temperature setback or system shutdown (SETBACK/BYPASS 30 °C) during unoccupied periods to prevent unnecessary energy use while maintaining a realistic indoor thermal behavior.

6.1 HRV system

6.1.1. HRV with air conditioning

Energy consumption has an annual pattern that is highly influenced by the season, especially due to air conditioning demand from the dry hot weather in Baghdad. The consumption of electricity drops to zero during the winter months. However, this usage grows at a steady rate starting in March. Then electric use peaks clearly in July and August. This is when the outside temperature is at its maximum. The electricity used for the compressor (cooling coil) makes up the majority of the building's total electricity use. The electricity use for the fan and cooling coils is much less than that for the compressor.

Furthermore, the electricity use for the fan nevertheless follows a similar season pattern. Moreover, the close association of total energy use with the compressor energy signifies space cooling is the foremost driver of total annual electrical demand in that room.

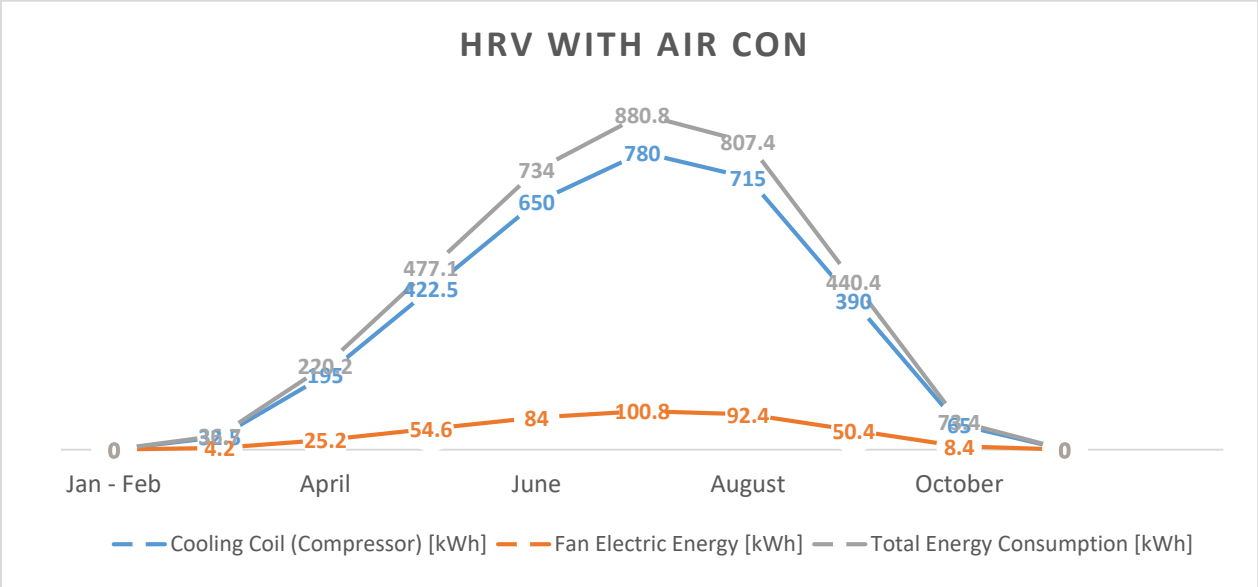


Figure 3: illustrates a line chart of HRV with air conditioning energy consumption

6.1.2. HRV with direct evaporative cooling

The Annual Energy/Water Use Profile for the HRV with Direct Evaporative Cooling Configuration, as seen in Figure 4, exhibits a significant seasonal pattern due to summer cooling demand. Fan electricity consumption increases in spring, peaks in July (due to maximum fan usage during outdoor temperatures), and decreases through October. The electrical energy used in compressor-based cooling systems is generally higher than that required for evaporative-process-based sensible cooling. Thus, there is lower electrical consumption accompanied by higher water consumption. These Behaviors Illustrate the Nature of the Inherent Energy-Water Trade-off Associated with Evaporative Cooling Systems in Hot-Dry Climates.

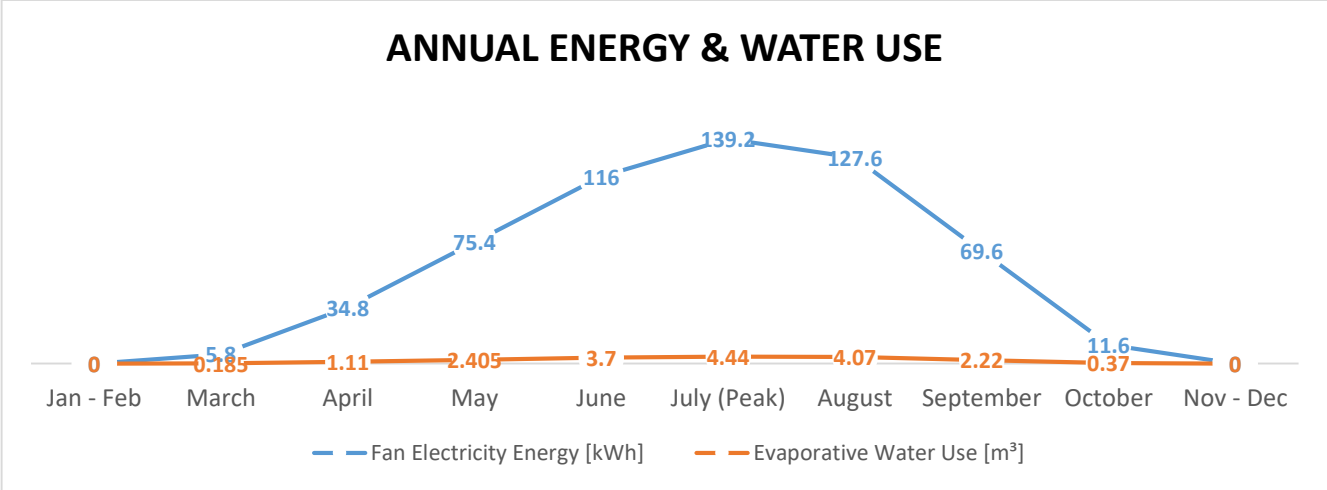


Figure 4: shows a line chart of HRV with evaporative cooling energy consumption

6.2 ERV system

6.2.1. ERV with air conditioning

As indicated in Figure 5, the annual energy use profile for ERV integrated with air conditioning has a significant seasonal variation due to cooling demand in the hot-dry climate of Baghdad. The sensible cooling delivered rises steeply from spring and peaks in July with rising outdoor temperature. The end use of total electrical energy consumption closely matches the electricity consumption trend of the cooling coil. This proves that cooling coil compressor-based cooling is the major end-use consumer of energy in the system. Fan electricity is a smaller but consistent share of total energy use. The ERV achieves a peak electrical demand reduction with respect to ventilation-only configurations through its preconditioning of the outdoor air coming to the building.

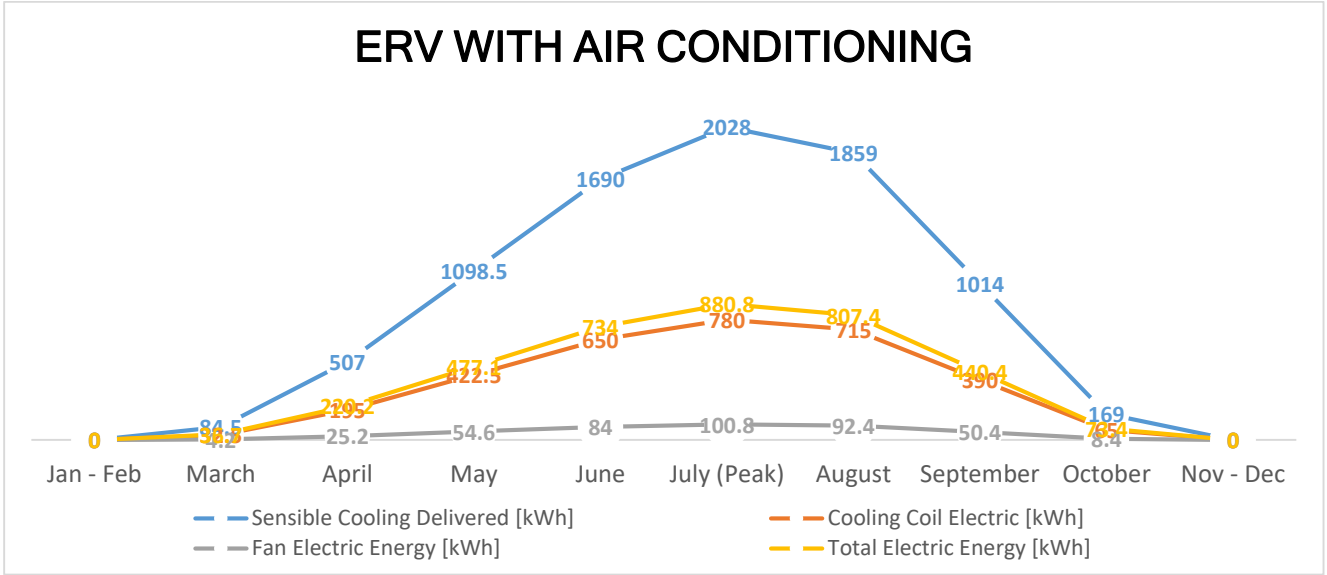


Figure 5: shows a line chart of ERV with air conditioning energy consumption.

6.2.2. ERV with direct evaporative cooling

The ERV that uses an evaporative cooling method has an extremely large and obvious trend for the number of times it operates per year, depending on when it is in its cooling mode and how much the outside temperature is. The ERV, as illustrated in Figure 6, does not consume electrical energy in terms of power input to the compressor; however, it consumes electricity to operate the fans. As such, the primary source of electrical energy consumption by the ERV is the operation of the fans. As the temperature rises throughout spring and into the middle of summer, the time spent running the fans also increases, reaching a peak in July, which is typically the hottest month. Conversely, during the summer months, the ERV greatly increases the amount of water it consumes to evaporate and cool the air entering the home (sensible cooling) compared to other months. This shows a clear electricity-water trade-off: as the amount of electrical energy used to operate the fans decreases, the amount of water evaporated to cool the air entering the house increases.

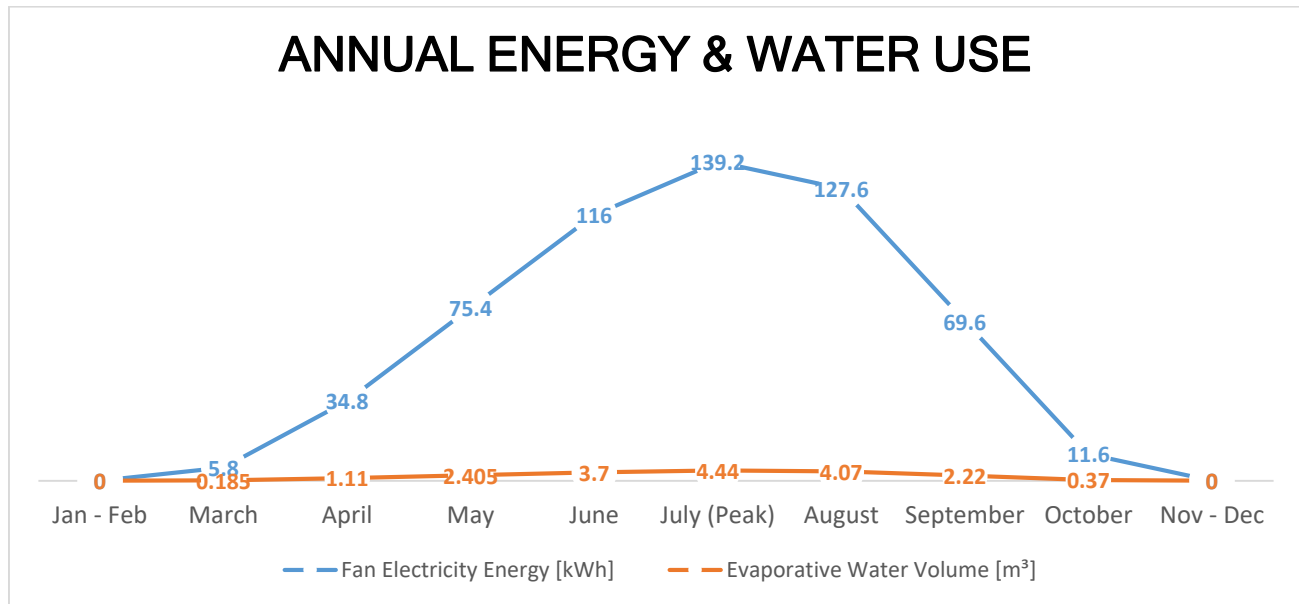


Figure 6: illustrates a line chart of ERV with evaporative energy consumption

6.3 Thermal comfort and indoor air quality (IAQ)

Thermal comfort and indoor air quality (IAQ) are significant parameters in buildings that affect occupant well-being and productivity [30]. The essential indicators for estimating these parameters are Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) [31]. PMV is an index predicting the thermal sensation of a large group of people on a seven-point scale that ranges from cold (-3) to hot (+3), with zero representing thermal neutrality. PPD is a related quantitative measure that estimates the fraction of people who are thermally dissatisfied. In Figure 7, a PMV range of -0.5 to +0.5 is considered the “comfort zone” for a satisfactory indoor environment.

Assessment of performance under peak load conditions is generally carried out for several mechanisms, such as Heat Recovery Ventilation (HRV) and Energy Recovery Ventilation (ERV), by mitigating these indices. The data show that systems using standard air conditioning achieve lower PPD and remain

within the PMV comfort band more consistently than those using evaporative cooling. This is in line with the findings in "Thermal Comfort & IAQ—Peak Summer Day.jpg." More specifically, the HRV with an evaporative cooling system shows high dissatisfaction, with a PPD value exceeding 20% during the hot peak at 15:00 hours. It shows how vital it is to choose system combinations that can control temperature and humidity to achieve thermal comfort and high IAQ.

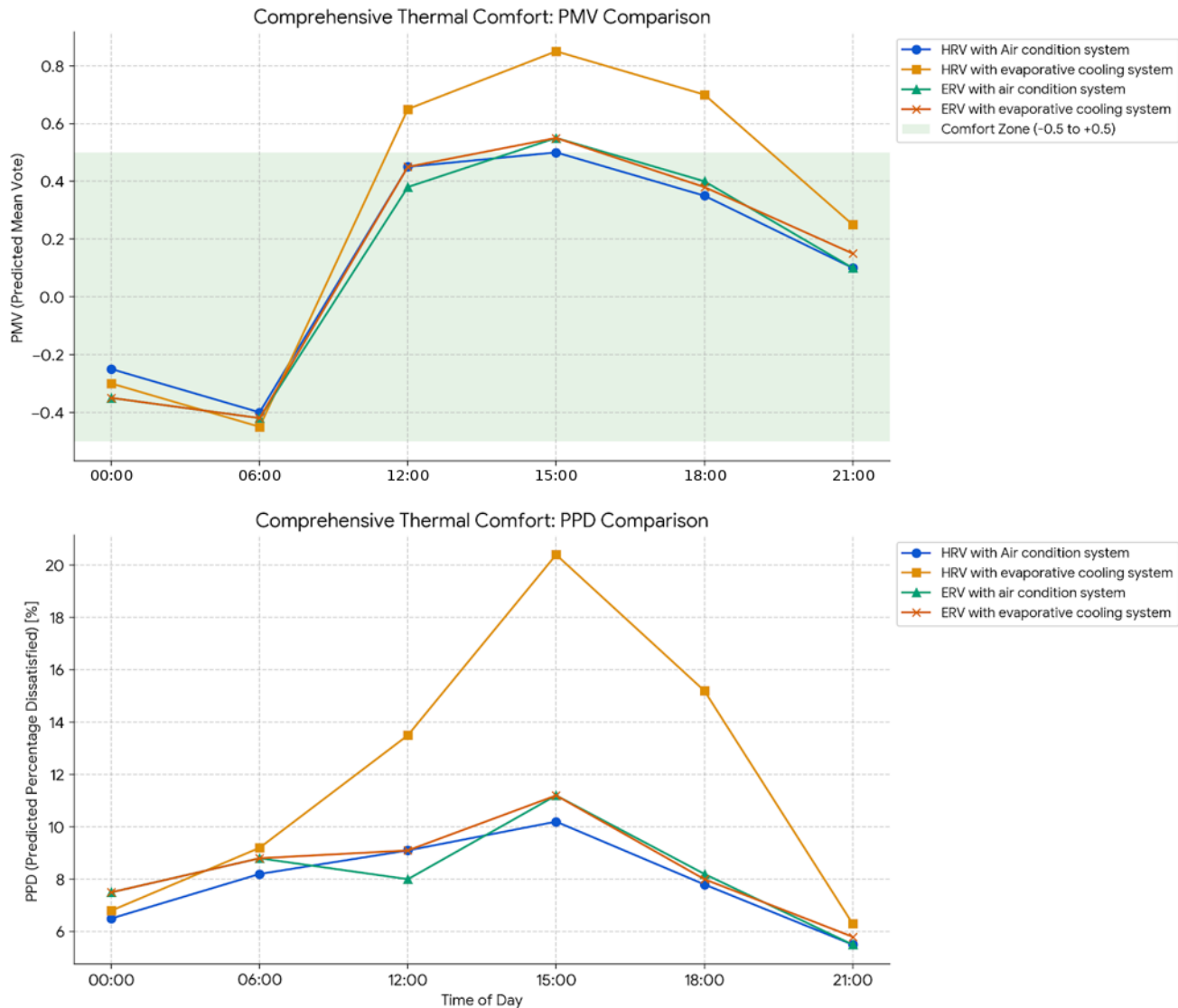


Figure 7: Thermal Comfort and Indoor Air Quality (IAQ) For All Scenarios

6.4 Heat and moisture recovery effectiveness:

The Comparative Performance: Sensible & Latent Energy Recovery shows the full-year energy recovery performances of four ventilation and cooling configurations. The scope of this assessment is the difference between sensible energy recovery, the transfer of dry heat, and latent energy recovery, which

is the handling of moisture or humidity. The largest share of total annual energy savings across all the systems studied is sensible energy recovery, which underpins the building.

Figure 8 shows that Energy Recovery Ventilation (ERV) systems perform much better than Heat Recovery Ventilation (HRV) units in moisture management. The ERV with the AC system configuration achieves the largest overall total energy recovery of about 1619 kWh/year. The latent energy recovery of 365 kWh/year in this system is notable, as it exceeds three and a half times that of the HRV in an AC setup. The HRV with the evaporative cooling system shows the highest individual sensible recovery at 1350 kWh/year. This is likely due to the thermal dynamics of the evaporative process. However, the HRV cannot achieve the same total energy savings as the ERV systems when heat and moisture recovery are considered.

Besides, the relatively stable air flow rates across all configurations suggest that these performance variations are linked to technology rather than air volume changes, and hence, ERV systems must be selected for applications where it is essential to control the humidity level.

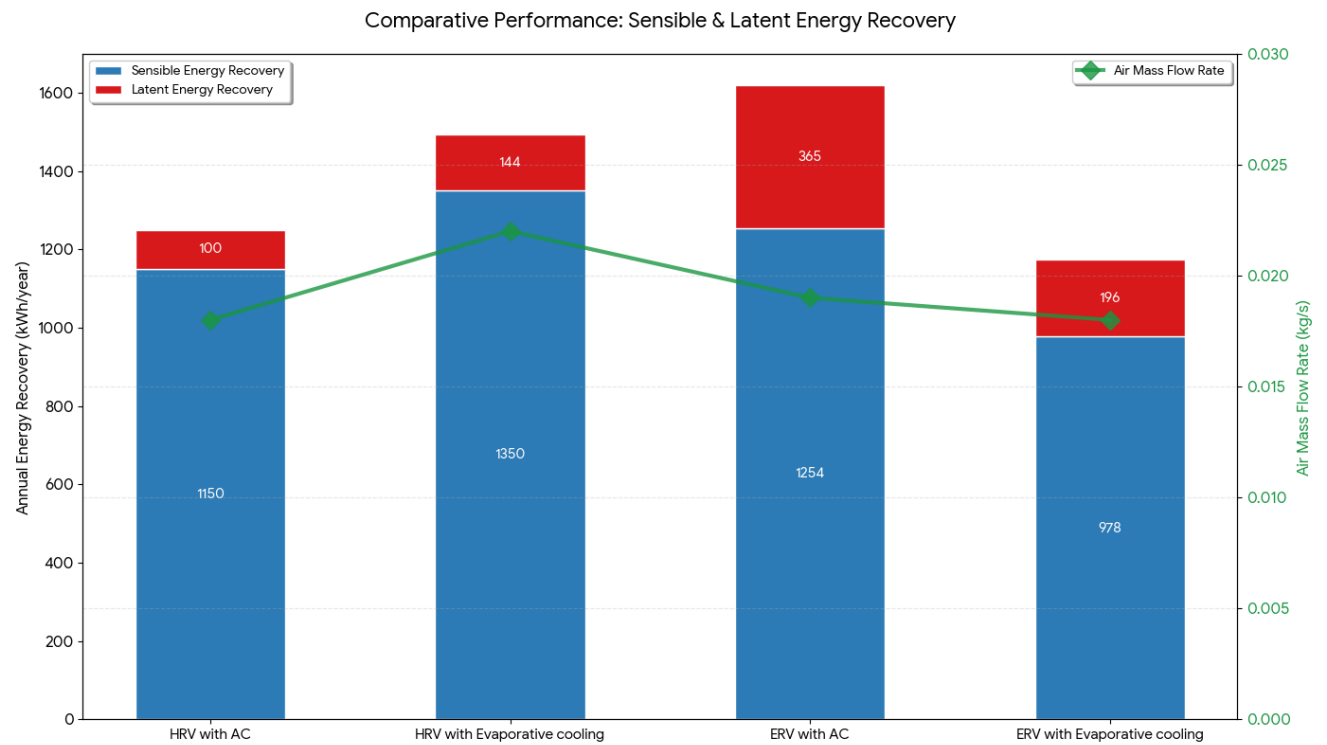


Figure 8: Comparison of Heat and Moisture Recovery Effectiveness for HRV and ERV Systems

6.5 Overall energy and water consumption comparison

Figure 9 provides a summary of the total energy and water consumption of the 4 HVAC configurations. The electrical energy demand of the HRV + AC configuration was the highest, then that of the ERV + AC configuration, whereas these evaporative-cooling configurations showed quite low electrical energy demand. ERV plus AC is estimated to use around 8.3% less electrical energy than HRV plus AC. The ERV evaporative-cooling configuration consumed somewhat less electrical energy and water than the HRV (4.44 m³ to 4.07 m³); moreover, the water quantity decreased. The results show that evaporative cooling involves an energy–water trade-off, further demonstrating that ERV also has the potential to improve moisture control. Moreover, it may reduce resource consumption.

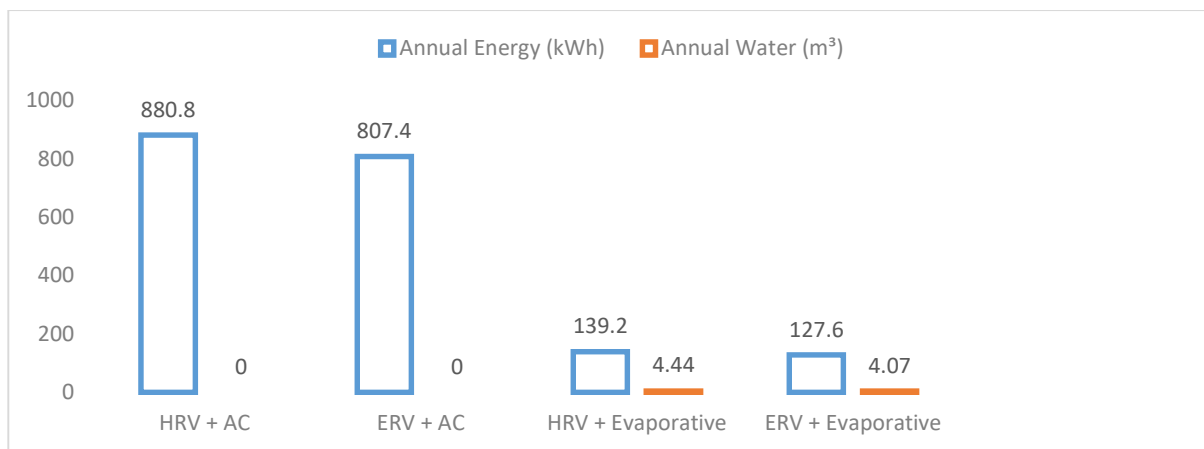


Figure 9: Annual energy and water consumption across different HVAC configurations.

7. Validation of simulation results

The energy simulation model for buildings presented in the thesis was validated using the published residential ventilation study conducted by Al-Naseri et al. (2023) [10] to assess its reliability. Validation focused on both quantitative agreements in terms of annual cooling energy demand and qualitative consistency of system performance trends, which are standard methods in building performance simulation (BPS) validations.

Annual electrical energy consumption comparisons show that the simulated configurations showed the same operating trend as those reported in the reference study. Both analyses found that systems incorporating energy recovery ventilation (ERV) will reduce cooling energy demand when compared with traditional ventilation systems; furthermore, evaporative-cooling-based configurations will significantly reduce electrical consumption while increasing water usage. More importantly, the relative ranking of system performance was the same in both studies, where ERV-assisted systems were found to have lower cooling energy demand than HRV-assisted systems in hot-dry climate conditions.

Quantitative comparisons of annual cooling-related energy demand show that there is a maximum deviation of approximately 27% between the simulation results and benchmark values, as shown in Figure 10. Although the deviation appears to be a large difference in absolute terms, this is consistent

with previously published comparative BPS studies. These studies often include differences in modeling scales, assumptions, simulation engines, and other factors that can lead to cooling-energy differences of greater than 25% when comparing models under similar boundary conditions. Studies of inter-model comparison also note that differences in assumptions for dynamic airflow, heat balance algorithms, moisture transfer formulations, and numerical solution procedures contribute to variation in cooling energy demand.

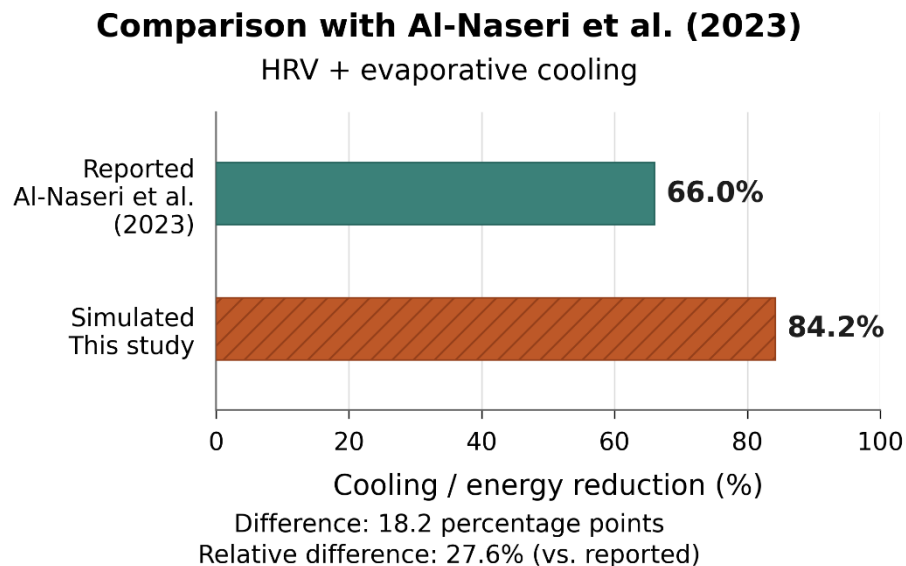


Figure 10: Validation of EnergyPlus results compared with the benchmark study by Al-Naseri et al. [10].

The remaining differences between the two studies can be attributed to several structural differences. The first difference is the geometric scale, where the current study examines a single-zone residential room ($\sim 20 \text{ m}^2$). and the reference study examined a full multi-zone dwelling ($\sim 200 \text{ m}^2$). Multi-zone buildings often exhibit greater interaction of thermal mass, internal heat distribution effects, and inter-zonal airflow coupling, affecting annual cooling demand. The second difference is that the current model has been designed to assume a very airtight envelope in order to assess the effect of controlled ventilation, heat, and moisture recovery. The reference study had infiltration rates representative of low-performance, typical residential buildings. The numerical discrepancies were also a result of variations in HVAC system representation, operational scheduling, and ventilation control logic.

To assess the model's robustness, a parametric sensitivity analysis was conducted, varying key input parameters over realistic residential ranges. The ventilation airflow rate was varied by $\pm 20\%$, the internal heat gains by $\pm 15\%$, and the envelope thermal transmittance within typical construction uncertainty limits. The annual cooling energy variation was moderate; this did not change the comparative performance ranking of HRV and ERV configurations in all tested cases, which were similar to the base case. As demonstrated, the model predictions remain stable; thus, the observed deviation is not due to numerical instability or sensitivity to parameters but to structural differences in the models of both studies.

This study aims to emphasise that the objective of validation for comparative design studies in building performance simulation is to achieve physical consistency and correct performance trends rather than agreement on numerical values. The existing model shows the same pattern of system performance, seasonal energy behavior, and humidity control trends as the benchmark reference; hence, this agreement is considered sufficient to show that the simulation framework is credible to assess ventilation-cooling strategies for hot-dry climates like Baghdad.

The HVAC performance comparison study has yielded certain outcomes that can be used in making conclusions about the validity of the simulation model used, as follows: a quantitative comparison, a structural explanation of modeling differences, and robustness test sensitivity evidence. Further details are present below.

8. Conclusions

The EnergyPlus software was used to compare four ventilation-cooling configurations for a single-zone residential space in Baghdad. The findings revealed that using energy recovery ventilation (ERV) with air conditioning lowered consumption of electrical energy by around 8.3% relative to heat recovery ventilation (HRV) with air conditioning and maintained a more stable indoor humidity. According to the new research, while evaporative-cooling systems used up to 50% less electricity than compressor-based cooling systems, they used more water. ERV configuration used slightly less electricity and water as compared to the HRV configuration and provided better humidity control. During peak summer hours, PMV and PPD values for the evaporative cooling configuration approached and exceeded the upper limits of thermal comfort, respectively. In general, results indicate that hot-dry climates exhibit an energy-water-comfort trade-off. The most consistent benefits in energy use and humidity management are provided by ERV. In contrast, evaporative cooling is more suitable where water availability is sufficient, and moderate thermal-comfort variation is acceptable.

Declaration of generative AI and AI-assisted technologies in the writing process

-None

Disclosures

The authors have no conflicts of interest to declare in relation to this manuscript.

Abbreviations

The following abbreviations are used in this manuscript:

AAC	Autoclaved aerated concrete
AC	Air conditioning
ACH	Air changes per hour
BPS	Building performance simulation
EC	Evaporative cooling
ERV	Energy recovery ventilation

HRV Heat recovery ventilation
 HVAC Heating, ventilation, and air conditioning
 IAQ Indoor air quality
 IEQ Indoor environmental quality
 IESVE Integrated Environmental Solutions Virtual Environment
 LED Light-emitting diode
 NIST National Institute of Standards and Technology
 PMV Predicted mean vote
 PPD Predicted percentage dissatisfied
 RH Relative humidity
 SHGC Solar heat gain coefficient

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تحسين جودة الهواء الداخلي وكفاءة الطاقة في المناخات الحارة الجافة: دراسة محاكاة معايرة لأداء أنظمة استرجاع الحرارة والطاقة في بغداد

الخلاصة: تتناول هذه الدراسة تحدي الحفاظ على جودة الهواء الداخلي (IAQ) مع تقليل الطلب على طاقة التبريد في المناخات الحارة الجافة، حيث تفرض درجات الحرارة الخارجية المرتفعة ومتطلبات التهوية المتزايدة أعباءً كبيرة على أنظمة التدفئة والتهوية وتكييف الهواء التقليدية (HVAC). وعلى الرغم من الاستخدام الواسع لأنظمة التهوية باسترجاع الحرارة (HRV)، فإن المقارنة بين أدائها وأداء أنظمة التهوية باسترجاع الطاقة (ERV)، ولا سيما عند دمجها مع التبريد التبخيري، لا تزال غير مدروسة بما يكفي في مناخات الشرق الأوسط، مثل مناخ بغداد. طُوّر نموذج محاكاة باستخدام برنامج EnergyPlus، جرت معايرته محلياً لتقييم أربعة أنظمة: HRV مع تكييف الهواء المنفصل (AC)، وERV مع AC، وHRV مع التبريد التبخيري المباشر (EC)، وERV مع EC. أُجري التحليل لحيز سكني نموذجي ذي منطقة حرارية واحدة تحت الظروف المناخية لبغداد، مع التركيز على استهلاك طاقة التبريد، والراحة الحرارية الداخلية، والتحكم بالرطوبة، واستخدام الموارد. أظهرت النتائج أن دمج ERV مع AC يخفض استهلاك الكهرباء لأغراض التبريد بنحو 8% مقارنةً بنظام HRV، نتيجة استرجاع الحرارة الكامنة وتحسين التحكم بالرطوبة. وحققت أنظمة التبريد التبخيري انخفاضاً تجاوز 80% في استهلاك الطاقة الكهربائية، مقابل زيادة استهلاك المياه. ومن بين هذه الأنظمة، أظهر ERV تحكماً أفضل بالرطوبة واستهلاكاً أقل قليلاً للمياه مقارنةً بنظام HRV، مما أدى إلى استقرار أكبر للراحة الداخلية خلال فترات الذروة الصيفية. وحافظت جميع الأنظمة على مستويات مقبولة من الراحة الحرارية خلال معظم ساعات الإشغال، رغم اقتراب أنظمة التبريد التبخيري من الحدود العليا للراحة في الظروف القاسية. وتبرز النتائج مفاضلة واضحة بين استهلاك الطاقة والمياه، وتبين أن ERV يوفر الحل الأكثر توازناً من حيث جودة الهواء الداخلي وكفاءة الطاقة والتحكم بالرطوبة في المناخات الحارة الجافة. وفي المقابل، يظل دمج HRV مع التبريد التبخيري خياراً عملياً باستهلاك منخفض جداً للطاقة في المناطق التي لا يمثل فيها توفر المياه عاملاً مقيداً. وتقدم هذه الدراسة إرشادات عملية لاختيار استراتيجيات التهوية والتبريد في الظروف المناخية القاسية.

الكلمات المفتاحية: محاكاة EnergyPlus؛ جهاز التهوية باسترجاع الحرارة (HRV)؛ جهاز التهوية باسترجاع الطاقة (ERV)؛ المناخ الحار الجاف؛ التبريد التبخيري المباشر.