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Energy analysis of the integration of HRV and direct evaporative cooling for energy efficiency in buildings: a case study in Iraq

Husham Al-Naseri[1*], Robert Fryer[2] and Ali Samir[3]

Abstract

Responding to climate change and adapting to global warming requires creative solutions. In Iraq, the most reliable and popular tool to have buildings cooled is airconditioning units (AC). While an evaporative cooler is not enough to achieve thermal comfort in a very hot climate, AC units consume a lot of energy which causes a significant load on the grid in Iraq resulting in increasing the emissions of CO_2. This paper investigates the potential energy-saving associated with adopting a new arrangement of heat recovery ventilation (HRV) unit and evaporative cooler to achieve thermal comfort with far less energy. Two sets of efficiencies of both HRV and the evaporative cooler have been considered, and two different envelope performances are also investigated. To properly size the proposed system, an iterative process has been used until the smallest size of the proposed system enough to cool the building is determined. The proposed system has achieved considerable energy savings comprising a reduction of up to 66% in the cooling load energy consumption and a reduction of up to 44% in the overall energy consumption.

Keywords Energy-saving cooling system, Energy efficiency, Cooling system and building envelope, Heat recovery unit (HRV), Evaporative cooler

1 Introduction

In light of the environmental impacts associated with climate change, the responsibility to reduce greenhouse gas emissions falls especially upon the building sector, which accounts for 37% of global CO_2 emissions and 34% of global energy consumption [1]. By 2021, the cooling energy load in buildings reached 16% of total energy consumption in buildings, and with projected increases in population, floor area, and living standards, the demand for cooling is expected to rise significantly. An increased energy demand will result in higher grid loads and increased CO_2 emissions. Thus, it is crucial to focus efforts on achieving higher efficiencies, implementing nature-based and passive cooling strategies, and exploring low-energy cooling system alternatives. To realize the 2030 net-zero energy scenario, a 50% increase in air conditioning efficiency is required [2, 3].

The selection and implementation of cooling systems and strategies in buildings depend on climate conditions. Hot and wet climates necessitate a different approach to cooling compared to hot and arid climates. Achieving higher energy efficiencies involves utilizing different types of cooling devices and strategies in various combinations [4–6]. This research proposes a novel arrangement of an evaporative cooler and a heat recovery unit (HRV) as an energy-saving cooling system designed for hot and arid climates, with a specific case study for the Iraq climate.

In Iraq, buildings account for 80% of electricity consumption [7]. During the cooling season, the country

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experiences electricity shortages due to the high load imposed by air conditioning units (ACs). Consequently, Iraqi citizens face limited electricity supply, with only 12 h of availability during summertime [8]. Reducing energy consumption for cooling purposes will significantly contribute to alleviating the grid load and reducing CO_2 emissions.

According to the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) Standards of 2013, the climate in Iraq is characterized as very hot and dry [9], with air temperatures reaching up to 48 °C during summertime. The average relative humidity stands at approximately 20%. The predominant cooling system in Iraq is the direct expansion air conditioning system, which, while capable of delivering the required thermal comfort, consumes a substantial amount of energy, thereby imposing high loads on the power grid.

Direct evaporative cooling presents itself as a low-energy cooling strategy suitable for hot and arid climates. Evaporative cooling strategies have been implemented in various ways and system types. The first approach involves a direct evaporative cooler, where air passes through a wet medium, causing the water to undergo a phase change to vapor. This process leads to a decrease in air temperature and an increase in relative humidity [10, 11]. The second approach is the indirect evaporative cooler [12, 13], where water is sprayed onto the condenser, allowing for air cooling without affecting the relative humidity of the supplied air. The third approach combines both direct and indirect evaporative coolers [5, 14], employing a two-stage cooling process. The first stage involves indirect evaporative cooling, followed by the supply of the cooled air to the second stage, where direct evaporative cooling takes place. This arrangement offers higher effectiveness. Furthermore, evaporative cooling has been integrated with other mechanical cooling systems, such as vapor compression systems [4]. In all cases, interventions involving evaporative cooling have resulted in considerable energy savings.

However, direct evaporative cooling alone is insufficient to achieve thermal comfort in Iraq, where temperatures can reach 48 °C [15, 16]. One challenge associated with direct evaporative coolers is the potential humidity build-up within the space. Consequently, direct evaporative coolers cannot be used in air-tight buildings, as continuous exhaust is necessary to prevent humidity accumulation.

HVAC standards require a minimum level of ventilation in buildings to ensure the health and comfort of occupants [9]. Ventilation poses an additional burden on heating and cooling systems [6]. Energy/heat recovery units are employed to provide necessary ventilation with minimal energy losses. Energy recovery units (ERVs) enable the transfer of both latent and sensible heat between the supplied air and the exhausted air. Heat recovery units (HRVs) specifically facilitate sensible heat exchange. In the case of HRVs, the moisture content in the supplied air remains constant [6]. Various types of energy recovery units are utilized for different purposes. The HRV, with its ability to decrease the supplied air temperature and maintain low relative humidity, proves to be particularly valuable for the proposed cooling system as air with low relative humidity can be further cooled using a direct evaporative cooler.

Extensive research literature exists on ERV and HRV systems. The potential for energy savings using ERV/HRV is influenced by multiple factors, including the cooling system, temperature set-point, supplied air flow rate, effectiveness of sensible and latent heat transfer of HRV/ERV, building envelope performance, and climate conditions [6, 17–28]. Hence, it is essential to define these factors within the model to ensure reliable results regarding the energy-saving potential of integrating these units [6].

Existing research investigates the impact of ERV/HRV units either alone or when coupled with other HVAC systems. In most cases, ERV/HRV units have been studied as separate supporting components of heating or cooling systems. For instance, coupling an HRV unit with an air-to-air heat pump resulted in energy savings during the heating season but increased energy consumption in certain cooling scenarios in various Canadian cities [6]. Another example is the Energy Recovery with Exhaust Air Evaporative Cooling (EREEC) system, where exhausted air is cooled using an evaporative cooler before being exhausted through an energy recovery unit. Due to the greater temperature difference between the supplied ventilation air and the exhausted air, the supplied air temperature is lower than it would be without using the evaporative cooler. This arrangement accounts for up to 13% energy savings [29]. This paper investigates the utilization of an HRV unit as a main integral part of the cooling system for the building.

The proposed system in this paper aims to couple an HRV unit with a direct evaporative cooler to achieve thermal comfort results comparable to those achieved with AC units but with significantly lower energy consumption. This integration can be achieved through two different configurations. The first configuration involves using both the HRV unit and the evaporative cooler separately, as depicted in Fig. 1. The second configuration involves passing the air supplied through the HRV unit directly through the evaporative cooler before releasing it into the room, as illustrated in Fig. 2. In the second scenario, the cold exhausted air passes through the HRV unit, allowing the supplied air to be cooled through sensible heat exchange. The HRV functions as the first stage

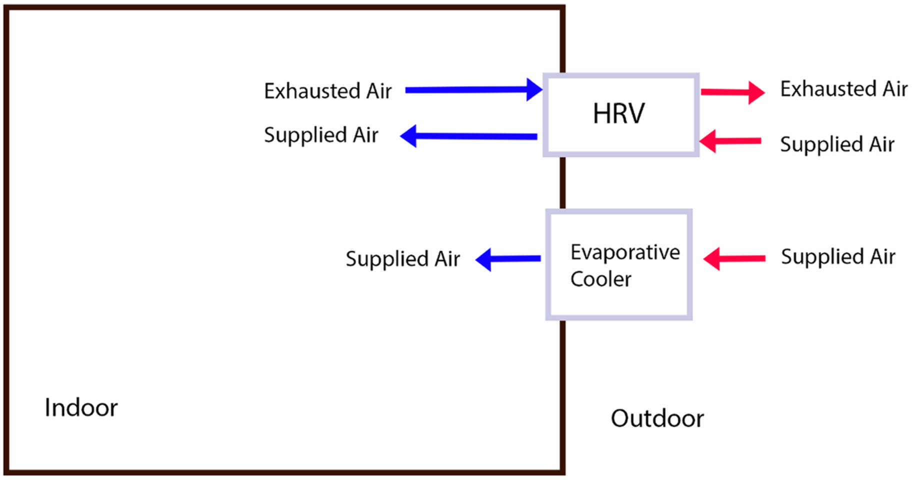

Fig. 1 Diagram of HRV unit and evaporative cooler working separately

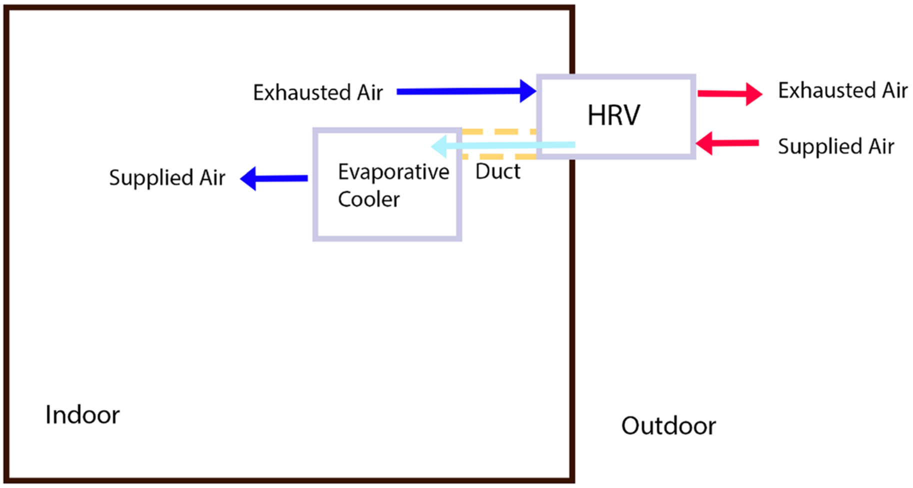

Fig. 2 Diagram of integrating HRV unit and evaporative cooler

of cooling. The cooled and dry air supplied by the HRV is then directly supplied through a duct to a direct evaporative cooler for further cooling before being distributed within the space. This research will specifically investigate the second scenario.

This system can be a better alternative for AC units for different reasons. First, it is anticipated that it would consume far less energy than air-conditioning units. Second, it will work as cooling device and humidifier at the same time in a dry climate while AC units causes dehumidifying already dry air. Third, it will provide more than enough ventilation without compromising the comfort or the energy consumption while AC units will require a separate ventilation system. Fourth, the proposed system does not compromise the airtightness of the building as the exhausted air quantity is approximately equal to supplied air.

2 Methods

In order to investigate energy-saving potential of the proposed system, an energy model for a residential unit has been developed using Integrated Environmental Solutions Virtual Environment (IESVE) software. A comparison between energy consumption of the building using AC units and energy consumption using suggested system will be made to estimate potential energy savings. The buildings are assumed to be in Al-Samawah, Iraq. The weather in Samawah is very hot and dry, and its ASHRAE climate zone is categorized as 1B [10]. The details of the energy model will be presented in this section.

2.1 Details of the residential unit

The house is a one floor building which includes a living room, a guest room, two bedrooms, a kitchen, and a corridor. The parcel dimensions are 20 m by 10 m. The built area of the unit is 200 m^2. The height is 3 m for all the spaces. Figure 3 presents the residential unit plan.

2.2 Envelope, plug load, occupancy, and internal gains details

The typical behavior of an Iraqi family has been considered, so plug load, internal load, and occupancy are defined in the model. Figure 4 presents the details of occupancy, plug load, and internal gains.

2.3 Envelope details

Two different envelope performances were investigated. First is the low-performance envelope which represents the most common building performance in Iraq [30]. The second is the high-performance envelope which represents the possible performance that would be adopted in Iraq in the near future. The details of the envelopes are presented in Table 1. For the low-performance envelope, infiltration is assumed to be 10 air change per hour (ACH) [31]. For the high-performance envelope, it is assumed to be 0.6 ACH.

2.4 System explanation

This section is dedicated to explaining all the aspects of the proposed system and how it was modeled using IESVE. The proposed system consisted of an HRV unit, duct, and evaporative cooler. The duct was used to convey the supplied air from the HRV unit to the evaporative cooler. Both the duct and the evaporative cooler were modeled to be inside the room.

2.4.1 HRV unit

In order to ventilate indoor spaces, different types of air-to-air energy recovery equipment were used. These units can recover both sensible and latent energy and were called the energy recovery unit. On the other hand, when it can recover only sensible heat, it is called the heat recovery ventilation unit. In this system, a HRV unit was used to prevent humidity from transporting between the exhausted air and the supplied air to maintain a low relative humidity of the supplied air. The reason for that was to maximize the effectiveness of the second stage of the proposed cooling system which was the evaporative cooler.

Various factors governed the energy consumption of these units. First was the Adjusted Sensible Recovery Efficiency (ASRE) which is an efficiency measurement unit used for energy modeling purposes. The efficiency was impacted by different factors, mostly the airflow pattern and direction of the exhausted air and supplied air. These patterns can be parallel flow with an efficiency of up to 50%, crossflow with an efficiency of up to 70%, counterflow with an efficiency of up to 100%, and a multiple

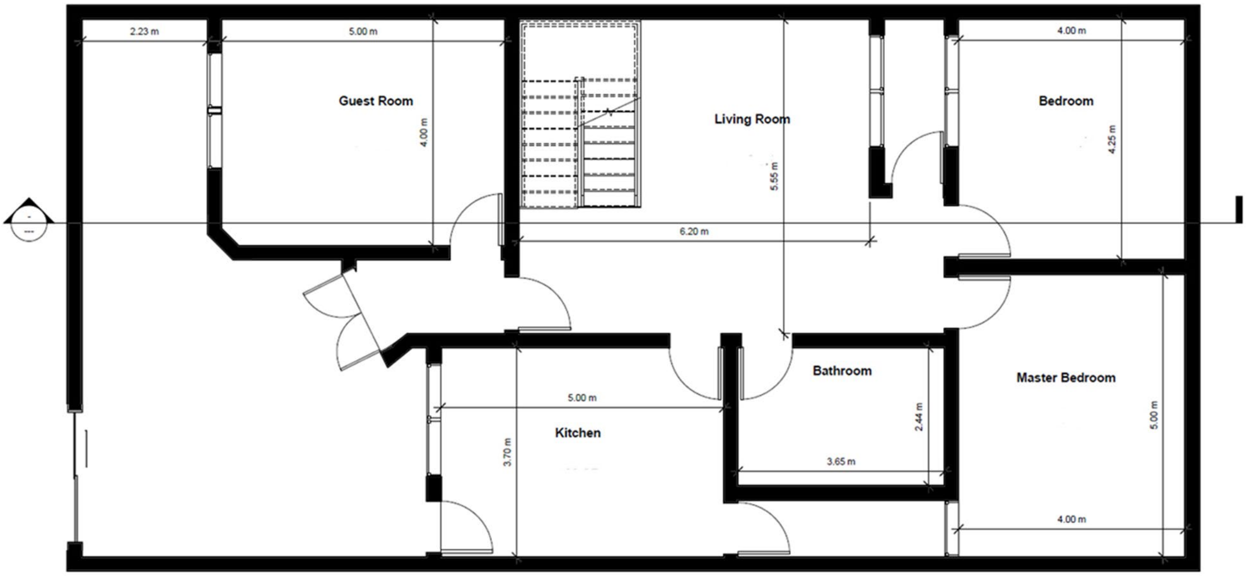

Fig. 3 The residential unit plan

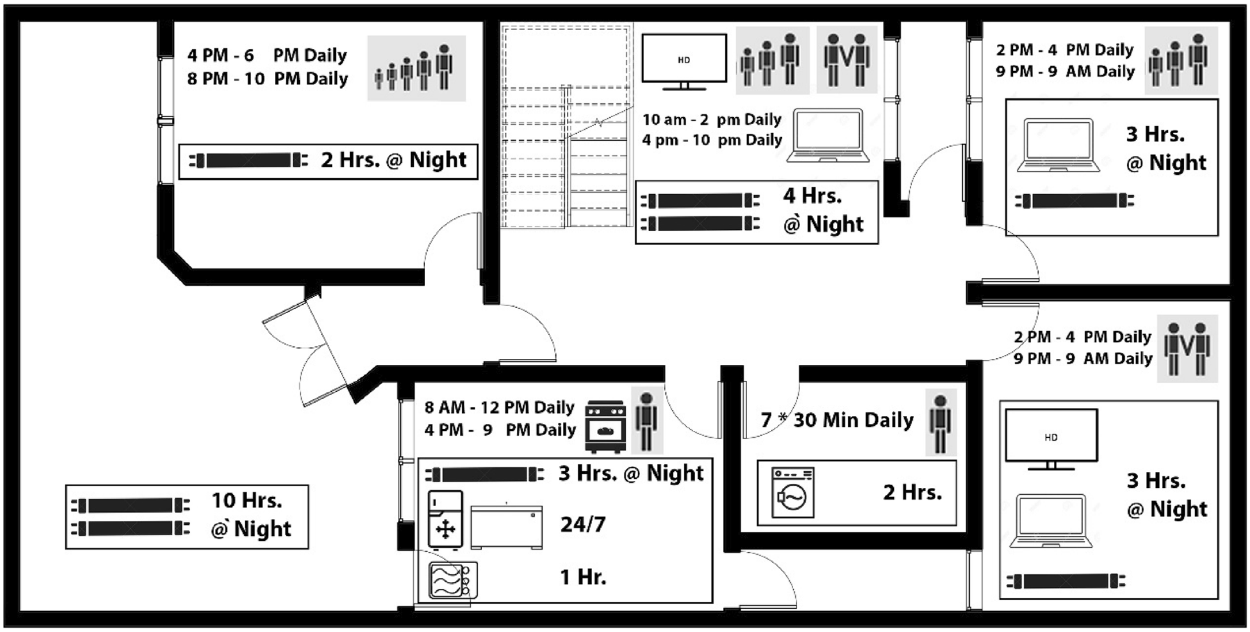

Fig. 4 Occupancy, plug load, and internal gain details

Table 1 Energy model envelopes details

Envelope	Roof insulation (*R* value) m^2. k/W	External wall insulation (*R* value) m^2. k/W	Floor insulation (*R* value) m^2. k/W	Windows *U* value m^2. k/W
Low-performance	0.18	0.46	0.044	0.17
High-performance	4.4	4.4	4.4	0.17

pass exchanger with an efficiency of up to 85% [32]. Since there are products in the market that have achieved an ASRE of 88% [33], an ASRE of 85% and 80% was considered in this paper.

2.4.2 Evaporative cooler

Evaporative cooling is a low-energy cooling strategy in hot and arid climates. Evaporative cooler alone is not enough to achieve thermal comfort in very hot climates [15, 16]. A direct evaporative cooler was used in the proposed system. The effectiveness of the evaporative coolers ranged from 50 to 95%. A random-media air cooler can easily achieve 80% effectiveness [32]. So, 80% and 90% effectiveness were considered in this paper.

2.4.3 Sensors and controllers

Given that the temperature set point, flow rate, air supply regime (constant or variable), and operation schedule can significantly impact the performance of the system, different control regimes were tested in this research to decide the optimum set in terms of energy consumption. There was one independent controller with a sensor in the system. This controller switched the system on and off or changed the flow rate (cubic meter per hour (m^3/h)) as per the tested control regime. The air supply regime considered in this paper was a constant air supply. The system switches off once the space temperature is below 23 °C. Two operation schedules were investigated. One was that the system works only when the space is occupied, which reflected the normal behavior of Iraqis. The second was that the system works continuously.

2.4.4 Duct

The duct was assumed to be inside the building and of a negligible length. Since the duct was inside the room there were no heat gains. Due to its small length, the energy consumption regarding moving the air through the duct was disregarded.

2.4.5 Thermal comfort conditions

Thermal comfort conditions were set to comply with ASHRAE Standard 55–2020. The targeted indoor temperature was 25 °C.

When the system is designed to have space temperature within the adaptive zone, the indoor temperature of 28 °C or below is still acceptable as it falls within adaptive thermal comfort. When the proposed systems failed to achieve the targeted temperature (25 °F), the baseline AC unit size was changed to match the level of thermal comfort achieved with the proposed system in order to achieve a fair and reliable energy-saving comparison.

2.4.6 Modeling the proposed system in IESVE

The APACHE HVAC tool was used to model the proposed and baseline systems for the purpose of dynamic simulation. To model the proposed system, three fans and one water pump were introduced. Two fans for the HRV were designed to supply and exhaust air at design capacity at an overall design pressure of 3.3 cm water with 80% motor efficiency. The fan for the evaporative cooler was designed to supply air at design capacity at an overall design pressure of 0.75 cm water and 0.1 KW water pump. No air filters were assumed in the system.

2.5 Process of sizing the proposed system

Given that there are many factors that impact the performance of the proposed system, in the beginning, it was the tests were mostly "trial and error." The purpose of this process was to develop a better understanding of the proposed system, a useful size, and to optimize the design. Later, a more systemic and organized process was used to determine the details and sizing of the system to achieve the best performance with the smallest system size. The factors were fixed and then changed one by one, multiple times, and changes were observed before altering others. The factors investigated in the model were as follows. First, was the temperature set point. Second was the range of temperatures below which the system switches off. Next, whether the supplied air is "variable air supply (VAS)" or "constant air supply (CAS)." It was concluded that the air supply regime is not of significant impact on the performance of the proposed system. So, CAS is considered for the simulations. The switch-off temperature for the proposed system was set at 23 °C, which was 2° below the targeted temperature due to the fact that the indoor air temperature was the reserve that supports the cooling process of the proposed system. The process of investigating the proposed system showed that the lower the indoor air temperature, the more resilient and energy-efficient the system. Finally, the sizing of the system took place.

2.6 Simulated cases

Eight simulations were run. SIM01 tested the baseline energy consumption of the low-performance envelope. SIM02 tested the energy model of the high-efficiency proposed system for a low-performance envelope.

The low efficiencies of the proposed system were also tested and are presented in SIM04. SIM04 failed to achieve less than 300 unmet hours despite increasing the size of the system multiple times. The indoor temperature was still within adaptive thermal comfort for SIM04. As a result, a new baseline cooling system sizing was identified for this case, presented in SIM03 in order to match the level of thermal comfort achieved with the proposed system in SIM04. The new system was also tested with the high-performance envelope in tests SIM05 through SIM08.

In all simulations (SIM01—SIM08), the proposed system switched on when the space was occupied and off when the space was unoccupied. Table 2 presents cooling system details for the simulations (SIM01 to SIM08).

While the cooling system for all the abovementioned simulations was working only while occupied, the proposed system was also tested when the system operates continuously regardless of the occupancy of the spaces. In this case, a smaller system is needed to achieve thermal comfort. The details of these simulations are presented in Table 3.

2.7 Limitations of the study

The efficiency of the HRV unit and flow rate are not constant and were impacted by different factors such as air temperature and overall pressure. In the simulations, efficiency and flow rate are assumed to be constant.

2.8 Energy model validation and reliability

IESVE is a building performance simulation (BPS) software that simulates whole building models. IESVE is capable of modeling and simulating complex HVAC systems with high accuracy. IESVE is approved for use by a wide range of codes, standards, methodologies, rating systems, and regulations. These approvals include the following:

- ASHRAE 140: 2001, 2004, 2007, 2014, 2017
- CIBSE TM33
- EU EN13791: July 2000
- ANSI/ASHRAE/ACCA Standard 183
- ISO 52000
- ASHRAE 90.1 Performance Rating Method (PRM): 2004/07/10/13/16/19
- ASHRAE 90.1 Energy Cost Budget Method (ECB): 2010/13/16
- ASHRAE 55 Calculation Procedure
- ASHRAE 62.1 Calculation Procedure
- CIBSE Guide A/ISO 7730 Calculation procedure
- UK National Calculation Methodology (NCM)
- Federal Incentives—IRS Code 179D
- California Energy
- Leadership in Energy and Environmental Design (LEED) building rating system [34]

The results of IESVE simulations have been validated with empirical data measured from a real-world project.

Table 2 Cooling system details for simulations (SIM01 to SIM08)

	HRV efficiency = 85% **Evaporative cooler efficiency = 90%**		**HRV efficiency = 80%** **Evaporative cooler efficiency = 80%**	
Low-performance envelope	**(SIM01)** Baseline cooling system ton (kW)		**(SIM03)** Baseline cooling system ton (kW)	
	Living room	5.5(19.34)	Living room	4.5(15.8)
	Bedroom	2.5(8.9)	Bedroom	2(7)
	Master bedroom	2.5(8.9)	Master bedroom	2(7)
	Guest room	5.5(19.34)	Guest room	4(14)
	(SIM02) Proposed system m^3/h		**(SIM04)** Proposed system m^3/h	
	living room	5950	Living room	5950
	bedroom	3400	Bedroom	3400
	master bedroom	3400	Master bedroom	3400
	guest room	3400	Guest room	3400
High-performance envelope	**(SIM05)** Baseline cooling system ton (kW)		**(SIM07)** Baseline cooling system ton (kW)	
	Living room	1(3.5)	Living room	0.8(2.9)
	Bedroom	0.5(1.8)	Bedroom	0.3(1.2)
	Master bedroom	0.5(1.8)	Master bedroom	0.3(1.2)
	Guest room	1(3.5)	Guest room	0.8(2.9)
	(SIM06) Proposed system m^3/h		**(SIM08)** Proposed system m^3/h	
	Living room	1100	Living room	1275
	Bedroom	550	Bedroom	600
	Master bedroom	550	Master bedroom	600
	Guest room	640	Guest room	1200

Table 3 Cooling system details for simulations (SIM09 to SIM0)

	HRV efficiency = 85% **Evaporative cooler efficiency = 90%**	
Low-performance envelope	**(SIM01)** Baseline cooling system ton (kW)	
	Living room	5.5(19.34)
	Bedroom	2.5(8.9)
	Master bedroom	2.5(8.9)
	Guest room	5.5(19.34)
	(SIM09) Proposed system m^3/h	
	Living room	2550
	Bedroom	1100
	Master bedroom	1100
	Guest room	1100
High-performance envelope	**(SIM05)** Baseline cooling system ton (kW)	
	Living room	1(3.5)
	Bedroom	0.5(1.8)
	Master bedroom	0.5(1.8)
	Guest room	1(3.5)
	(SIM10) Proposed system m^3/h	
	Living room	935
	Bedroom	425
	Master bedroom	425
	Guest room	425

This case study took place at the University of Strathclyde as part of the "Empirical Whole Model Validation Twin House Experiment for the IEA-ECB Programme's Annex 71 Project" [35].

Another research was undertaken to compare the results of IESVE with EnergyPlus (another BPS software that simulates the physical models and HVAC systems). The results of simulations of these two software were close [36].

3 Results and discussion

After running the simulations, both the energy consumption levels and numbers of unmet hours were calculated. In all cases, significant energy savings were achieved. Table 4 presents the results of the energy simulations and the associated energy savings.

Due to the low-performance envelope and the high efficiencies of both HRV and the utilized evaporative cooler in SIM01 and SIM02, the overall energy saving was found to be 44%, while the saving in terms of the cooling load was 56.7%. Lower energy savings were observed in relation to the lower system efficiencies. Indeed, a 36.4% overall energy saving and a 47.9% reduction in the energy required for cooling were observed with regard to SIM03 and SIM04.

Table 4 Results of the energy simulations and the associated energy savings (SIM01 to SIM08)

	HRV efficiency = 85% **Evaporative cooler efficiency = 90%**				**HRV efficiency = 80%** **Evaporative cooler efficiency = 80%**			
Low-performance envelope baseline system **SIM01,03**	**SIM01**				**SIM03**			
	Unmet Hrs	189	Overall energy savings, %	44%	Unmet Hrs	170	Overall energy savings, %	36.40%
	Energy MWh	20.94			Energy MWh	65.7		
Low-performance envelope proposed system **SIM02,04**	**SIM02**				**SIM04**			
	Unmet Hrs	186	Cooling load energy cut, %	56.70%	Unmet Hrs	135	Cooling load energy cut, %	47.90%
	Energy MWh	11.72			Energy MWh	41.76		
High-performance envelope baseline system **SIM05,07**	**SIM05**				**SIM07**			
	Unmet Hrs	227	Overall energy savings, %	31%	Unmet Hrs	135	Overall Energy Savings %	27.30%
	Energy MWh	8.75			Energy MWh	29.05		
High-performance envelope proposed system **SIM06,08**	**SIM06**				**SIM08**			
	Unmet Hrs	191	Cooling load energy cut, %	66.30%	Unmet Hrs	62	Cooling load energy cut, %	60.80%
	Energy MWh	6.05			Energy MWh	21.12		

When the high-performance envelope was utilized, considerable energy savings were achieved. In fact, when coupled with the high efficiencies, a 31% overall energy saving was achieved, as was a 66.3% reduction in energy consumption with regard to the cooling load (SIM05 and SIM06). Lower overall energy savings but higher energy savings in terms of the cooling load were achieved using the high-performance envelope when compared with the low-performance envelope. The decrease in the overall energy saving stemmed from the fact that the weight of the cooling load within the overall energy consumption was less in relation to the high-performance envelope than the low-performance envelope, which led to the associated savings. By contrast, the reduction in the energy consumption required for cooling was significantly higher in relation to the high-performance envelope when compared with the low-performance envelope. Due to the lower efficiencies in SIM07 and SIM08, lower energy savings were observed. In fact, a 27.3% overall energy saving and a 60.8% reduction in the cooling load were achieved.

It was found that the size of the proposed system played an important role in determining its efficiency, cost, and footprint. As a result, downsizing the unit could prove beneficial. Thus, another possibility was explored. As the proposed system was highly dependent on the indoor temperature, the possibility of maintaining the indoor temperature within a targeted range by running the system continuously was explored. One important finding was that smaller-sized systems could be used to achieve thermal comfort. In terms of the energy savings, the results differed between the two envelopes. Table 5 presents the details concerning the two simulations. With regard to the high-performance envelope, a lower overall energy saving (14%) and a lower reduction in the cooling load energy (33.44%) were achieved when compared with the energy savings revealed by SIM04. In terms of the low-performance envelope, the energy savings were approximately equal to those seen in relation to SIM02, although smaller-sized units were involved. These results suggest a degree of flexibility when it comes to choosing design solutions.

Table 5 Cooling system details for the simulations (SIM09 and SIM10)

	HRV efficiency = 85% **Evaporative cooler efficiency = 90%**			
Low-performance envelope baseline system SIM01	Unmet Hrs	189	Overall energy savings, %	44.80%
	Energy MWh	20.94		
Low-performance envelope proposed system SIM09	Unmet Hrs	162	Cooling load energy cut, %	57.73%
	Energy MWh	11.56		
High-performance envelope baseline system SIM05	Unmet Hrs	227	Overall energy savings, %	14.00%
	Energy MWh	8.75		
High-performance envelope proposed system SIM10	Unmet Hrs	237	Cooling load energy cut, %	31.44%
	Energy MWh	7.27		

4 Conclusions

The proposed system can potentially achieve considerable energy savings comprising a reduction of up to 66% in the cooling load energy consumption and up to 44% in the overall energy consumption.

The efficiencies of the utilized cooling units represent an essential factor concerning the potential energy savings. While the high efficiencies achieved in the simulations targeted thermal comfort, the low efficiencies failed to provide an indoor temperature below the target temperature, although the provided temperature was still within the adaptive thermal comfort zone.

Another important factor concerns the operating schedule of the system. Keeping the system working continuously versus working only when the space is occupied offers a number of benefits. First, a smaller-sized system can be used. Second, the unpredictable behavior of the occupant will no longer prove a challenge. Finally, in terms of a continuously operating system, similar energy savings were achieved compared with a system that only operated during the hours of occupancy in the low-performance envelope, while far fewer energy savings were achieved in the high-performance envelope than a system in limited operation.

Authors' contributions

The conception of this research project was initiated by the first author, and the collaborative research effort was conducted collectively, with all authors making equal and substantial contributions throughout the entirety of the study, up to the point of submission

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Availability of data and materials

The data availability for this research paper is as follows: all data utilized in this study is readily available. The datasets used are publicly accessible or can be obtained upon request from the corresponding author. The authors confirm that there are no restrictions on data availability, and all relevant information required to replicate the findings is provided within the manuscript.

Declarations

Competing interests

The authors declare that they have no competing interests.

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