sustainability

MDPI

Article

Controlled Night Ventilation for Cooling-Demand Reduction in Bahraini Residential Buildings: A Mixed-Mode Simulation Study

Ali Sedki

Department of Civil and Architectural Engineering, Faculty of Engineering, Applied Science University, Al Ekir 3201, Bahrain; ali.ali@asu.edu.bh

Abstract

Residential electricity demand in Bahrain is strongly shaped by long cooling seasons, high air-conditioning dependence and the operation of standardised housing typologies. This paper evaluates the energy and comfort implications of applying a controlled night-ventilation mixed-mode strategy to a representative Bahraini Ministry of Housing residential unit. The study compares two DesignBuilder/EnergyPlus scenarios: S0, a replicated closed-window baseline with split air-conditioning at a 24 °C cooling setpoint, and S1, a controlled mixed-mode case in which windows are available only during night-time periods when outdoor conditions are suitable for passive cooling. The base model is grounded in a published and validated Bahraini residential dataset containing geometry, construction properties, schedules, HVAC assumptions and monthly electricity bills, and was cross-checked against this dataset (see Methods for the monthly error statistics used to qualify this comparison). The replicated baseline produced 34,729.46 kWh/year, which differs from the published reference value of 34,720.19 kWh/year by only 0.027%. The S1 case reduced annual simulated electricity consumption to 33,593.04 kWh/year, corresponding to a saving of 1136.42 kWh/year, or 3.27% relative to S0. The benefit was highly seasonal: January, February, March and December accounted for 96.2% of the annual saving, while May to September showed no meaningful reduction. Hourly January outputs showed 425 zero-cooling hours out of 744 h (57.1%), cooling electricity of 87.32 kWh and a mean operative temperature of 23.81 °C. January thermal-comfort indicators (mean PMV +0.94; only 0.5% of hours within the ±0.5 PMV band) show that the strategy delivers real electricity savings but does not, on the PMV metric, guarantee acceptable comfort in every hour; the strategy is therefore best understood as a seasonal, humidity-aware operational measure that reduces cooling electricity in cooler months while carrying a thermal-comfort trade-off that requires either a tighter control-temperature threshold or explicit acceptance of a wider comfort range. Because the strategy yields no savings during the peak summer months, it should be positioned as a complement to—not a substitute for—envelope and HVAC-efficiency upgrades, and its economic case under Bahrain's subsidised electricity tariff is modest and is presented here as indicative potential rather than a demonstrated payback benefit. By reducing residential cooling electricity without requiring building-fabric retrofit, the findings support the United Nations' Sustainable Development Goals (SDGs), particularly SDG 7 (affordable and clean energy), SDG 11 (sustainable cities and communities) and SDG 13 (climate action), by contributing to sustainable, low-carbon operation of the residential building stock in hot–arid Gulf climates.

Check for updates

Academic Editors: Giouli Mihalakakou and Tareq Abuimara

Received: 25 June 2026
Revised: 2 August 2026
Accepted: 3 August 2026
Published: 9 September 2026

Copyright: © 2026 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license.

Keywords: mixed-mode ventilation; cooling demand; thermal comfort; hot–arid climate; occupant behaviour; sustainable buildings

1. Introduction

Building operations are a critical part of the global energy and climate agenda. The International Energy Agency reports that building operations account for around 30% of global final energy consumption and 26% of global energy-related emissions, while the Global Status Report for Buildings and Construction identifies building-energy codes, low-carbon operation, renewable energy integration and climate-responsive design as central priorities for decarbonizing the built environment [1,2]. Reducing residential cooling-related electricity use in this way directly supports Sustainable Development Goal 7 (affordable and clean energy), Goal 11 (sustainable cities and communities) and Goal 13 (climate action) by lowering household energy demand and associated carbon emissions without requiring costly infrastructure change. These pressures are intensified in hot and arid regions, where long cooling seasons, solar exposure and high expectations of indoor comfort make air-conditioning a dominant end use [3,4].

The Gulf Cooperation Council (GCC) region is one of the most demanding contexts for cooling-demand reduction. Studies of Bahrain and neighbouring Gulf countries show that residential electricity demand is strongly affected by air-conditioning, household occupancy, fuel/electricity subsidies, envelope performance and lifestyle expectations [5–8]. In Bahrain, Elnabawi (2021) reported that residential buildings accounted for 48.6% of national electricity consumption in 2016 and that electricity use rises sharply during the hot season [9]. Elnabawi (2021) further reported that residential air-conditioning can approach 80% of peak residential power demand [9]. These studies demonstrate why cooling-demand reduction in Bahraini dwellings is both an energy-efficiency and planning-policy concern.

Many technical responses to hot-climate residential energy demand emphasise envelope insulation, glazing, shading, cool roofs, green roofs, efficient HVAC systems and building-energy codes [9–15]. At the urban scale, softscape interventions such as strategic vegetation placement and green infrastructure have also been shown to mitigate urban heat island effects and improve outdoor thermal conditions in hot–arid climates [16,17]. These measures are essential; however, actual residential performance is also shaped by operation. Occupants decide when to open windows, close doors, use shading, switch on cooling and tolerate a wider or narrower range of indoor conditions [18–21]. Therefore, passive and low-energy cooling strategies should be evaluated not only as physical design measures but also as controlled operational strategies.

Adaptive thermal comfort theory provides the conceptual basis for this operational perspective. The adaptive model argues that occupants are not passive recipients of thermal conditions; they adapt physiologically, psychologically and behaviourally through clothing adjustment, air movement, window opening and expectations of control [22–25]. Mixed-mode ventilation translates this theory into operation by combining natural ventilation and mechanical cooling, using outdoor air when it is beneficial and reverting to air-conditioning when outdoor conditions become unsuitable [26–28].

In hot–arid and Gulf climates, the main challenge is not whether windows can be opened, but when they should be opened. Daytime ventilation may introduce hot air and increase cooling demand, while night ventilation may remove stored heat when outdoor conditions are cooler [29–32]. Sedki et al. (2019) showed that cross night-purge ventilation was the best-performing summer comfort strategy among tested window-opening behaviours in a Cairo residential case [33]. Elnabawi and Saber (2022) and Al

Niyadi and Elnabawi (2025) also found that hybrid ventilation in arid climates produces stronger savings during cooler seasons than during hot months [13,34]. These findings suggest that ventilation should be treated as a climate-sensitive control problem, not as a fixed open-window assumption.

Despite the growing literature on adaptive comfort, passive cooling, mixed-mode ventilation and GCC building energy performance, three gaps remain. First, much of the Bahraini residential literature has focused on code-based envelope measures and roof technologies rather than occupant-controlled mixed-mode operation. Second, many hybrid-ventilation studies in arid climates focus on offices or educational buildings, while residential operation remains less examined. Third, annual energy-saving indicators can hide the months and hours when night ventilation is actually useful. A fourth, methodological gap concerns the fact that prior single-case Bahraini simulations have rarely reported the monthly error statistics required by ASHRAE Guideline 14 to qualify a base-case model as calibrated against measured billing data and have rarely distinguished a fully automated mixed-mode control strategy from a simple occupant behavioural guideline in terms of feasibility and cost [35]. This paper addresses these gaps by evaluating a two-scenario model for a representative Bahraini residential unit: a validated closed-window base case and a controlled night-ventilation mixed-mode case.

The objectives are to: (1) check the replicated base-case model against measured monthly electricity data using ASHRAE Guideline 14 monthly error statistics; (2) quantify annual and monthly electricity differences between the base case and controlled night-ventilation case; (3) identify the months in which night ventilation provides meaningful reduction; (4) examine January hourly cooling behaviour, end-use electricity and heat-balance patterns; and (5) interpret the results for residential design, planning practice and policy integration. The contribution is a focused, time-sensitive evaluation of controlled night ventilation as a seasonal operational strategy for Bahraini residential cooling-demand reduction.

2. Literature Review

2.1. Adaptive Comfort and Occupant-Controlled Operation

Thermal comfort research has developed from steady-state heat-balance models toward adaptive interpretations of comfort. The predicted mean vote/predicted percentage dissatisfied model developed by Fanger (1970) remains foundational and is embedded in ISO 7730, while ASHRAE Standard 55 and EN 16798-1 distinguish between fully mechanically conditioned spaces and naturally conditioned or mixed-mode spaces where occupants have opportunities for environmental control [36–40]. This distinction is important for the present study because the base case represents a closed-window, mechanically cooled residential condition, whereas the controlled night-ventilation case introduces an occupant-controlled mixed-mode operation. Therefore, thermal comfort cannot be interpreted only as a fixed cooling setpoint or annual energy reduction; it must also be assessed through indoor operative temperature, humidity conditions, and comfort indicators during the hours when mechanical cooling is reduced or switched off.

Adaptive comfort theory argues that occupants are not passive recipients of indoor thermal conditions. Instead, they respond to discomfort through behavioural, physiological, and psychological adaptation, including window opening, clothing adjustment, fan use, shading control, changes in activity, and acceptance of wider indoor temperature ranges when environmental control is available [22,23,41–43]. This is especially relevant in residential buildings, where occupants usually have more direct control over windows, doors, curtains, clothing, and daily routines than in centrally managed commercial buildings. For this reason, window operation should not be treated as a secondary modelling detail. It is a central variable linking energy performance, indoor air quality, and thermal comfort.

Previous studies confirm that occupant-controlled ventilation can substantially alter comfort outcomes in hot–arid residential settings. Sedki et al. (2019) examined several behavioural window-opening scenarios and showed that comfort performance varied according to season, timing, and ventilation mode [33]. Their results indicated that cross night-purge ventilation produced the strongest improvement in summer comfort, while short window opening was more relevant for winter fresh-air intake than for thermal improvement. This supports the central assumption of the present study: the effectiveness of ventilation depends less on opening windows in general and more on opening them at the correct time and under suitable climatic conditions. Sedki et al.'s envelope-retrofit and ventilation study reached a similar conclusion, showing that the combination of envelope measures and night-purge ventilation improved summer comfort more effectively than insulation alone, while also warning that closed or poorly controlled strategies can trap internal heat gains indoors [44].

The present study applies this adaptive logic to a Bahraini residential case, but it evaluates comfort differently from a purely free-running natural-ventilation study. Because the building remains mechanically cooled when outdoor conditions are unsuitable, the S1 scenario is interpreted as controlled mixed-mode operation, not as continuous natural ventilation. Accordingly, comfort is examined through three complementary indicators. First, operative temperature is used to describe the indoor thermal condition experienced by occupants, because it reflects the combined influence of air temperature and radiant exchange. Second, PMV/PPD outputs are used as diagnostic indicators to compare the mechanically cooled and mixed-mode conditions, while recognising that their interpretation depends on assumptions about the clothing level, metabolic rate, air speed, and occupancy. Third, relative humidity and latent-load behaviour are examined because night ventilation in Bahrain may reduce sensible cooling demand while still creating humidity-related discomfort or latent cooling penalties.

This combined comfort interpretation is important because the energy results alone do not prove comfort acceptability. In the January mixed-mode analysis, for example, the reduction in cooling operation must be read together with operative temperature, PMV/PPD, and humidity outputs. A zero-cooling hour indicates that mechanical cooling was not required by the model at that time, but it does not automatically prove that the space was comfortable or that windows were open. For this reason, the study treats thermal comfort as a multi-variable outcome rather than a simple consequence of reduced cooling electricity. This approach is consistent with simulation-based comfort validation studies in hot–arid residential buildings, where indoor temperature, humidity, and occupant operation were used to assess the reliability of predicted indoor conditions.

Hybrid and mixed-mode ventilation studies in arid climates further support this approach. Elnabawi and Saber (2022) argued that hybrid systems are valuable because they switch to mechanical cooling when natural ventilation is not possible, allowing energy reduction without compromising thermal comfort [13]. Their results also showed that hybrid ventilation performs better during cooler seasons than during hot periods, which reinforces the need for monthly and hourly comfort analysis rather than relying only on annual averages. Similarly, Elnabawi (2025) reported that hybrid ventilation in an arid-climate case study achieved stronger savings in cooler seasons than in hotter months, confirming that mixed-mode performance is seasonal and control-dependent [41].

Based on this literature, the present paper positions controlled night ventilation as an adaptive operational strategy rather than a fixed passive-cooling solution. The strategy is expected to be useful only when outdoor night-time conditions can reduce indoor sensible heat without introducing excessive humidity. Therefore, the comfort analysis in this study focuses not only on whether annual electricity consumption decreases, but also on whether

the mixed-mode scenario maintains acceptable operative temperature, avoids humidity-related discomfort, and identifies the specific months and hours when occupants can rely less on mechanical cooling.

2.2. Natural Ventilation, Night Purge and Ventilative Cooling

Natural ventilation can contribute to cooling-demand reduction through direct comfort cooling and night-purge cooling. Direct comfort cooling increases air movement around occupants, while night-purge cooling removes heat stored in the building fabric during cooler hours [31,45–48]. The climatic potential of night ventilation depends on the indoor–outdoor temperature difference, wind availability, thermal mass, internal gains and control timing [29,49–51].

Several studies show that night ventilation can be effective but conditional. Blondeau et al. (1997) and Geros et al. (1999) [30,49] demonstrated the potential of night ventilation for reducing summer overheating, while Shaviv et al. (2001) [32] showed that night ventilation and thermal mass can operate together as a passive cooling strategy. Oropeza-Perez and Østergaard (2014) [52] emphasised that natural ventilation can reduce energy use under warm conditions, but only when climatic and operational constraints are respected. In hot climates, uncontrolled daytime ventilation can increase indoor heat gains, so control logic is as important as opening area [31,53].

Residential evidence from hot–arid contexts is particularly important. Sedki et al. (2019) [33] evaluated occupant behavioural ventilation strategies in Cairo and found that cross night-purge ventilation gave the highest summer comfort benefit among the scenarios tested. A related study on hot–arid social housing showed that combining envelope measures with natural ventilation behaviour improved summer comfort more strongly than insulation alone [44]. By contrast, work cited by Gado and Osman (2009) [54] indicates that passive ventilation effects can be limited in some desert-housing configurations. These mixed outcomes justify local testing rather than transferring results directly from one hot climate to another.

2.3. Hybrid and Mixed-Mode Ventilation in Arid Climates

Hybrid or mixed-mode ventilation provides a practical framework for hot climates because it does not assume that natural ventilation can provide year-round comfort. Instead, the building uses natural ventilation when outdoor conditions are favourable and mechanical cooling when they are not [26,27,55]. This is relevant to Gulf housing because air-conditioning remains necessary during the long hot season, but cooler months and night-time periods may allow temporary reduction in cooling operation.

Studies in arid and warm climates support this seasonal interpretation. Ezzeldin and Rees (2013) [28] found that mixed-mode ventilation and low-energy cooling systems have potential in arid office buildings. Daaboul et al. (2018) [56] assessed mixed-mode ventilation and air-conditioning in Beirut and showed that energy benefits depend on climate and future weather assumptions. Annan et al. (2014) [57] examined natural ventilation in Beirut residential buildings and highlighted the role of comfort-hour extension. Elnabawi and Saber (2022) [13] reported 23% annual savings for a hybrid ventilation strategy in a hot–arid educational building, with higher savings in cooler seasons than hot periods. Al Niyadi and Elnabawi (2025) [34] similarly reported 23% annual savings and 20% carbon-emissions reduction in a Dubai case study, with greater savings during cooler seasons.

These studies indicate that mixed-mode ventilation should be evaluated through seasonal and hourly analysis, not only annual totals. Annual savings can appear modest in severe climates because the strategy is inactive during peak summer, yet the strat-

egy may still be valuable during selected months if it reduces cooling run time without compromising comfort or humidity control.

2.4. Simulation Credibility, Validation and Performance Metrics

Dynamic building-performance simulation is widely used to evaluate cooling strategies, but its credibility depends on transparent inputs and validation. EnergyPlus and DesignBuilder are widely used for building energy simulation, and their credibility rests on first-principles heat-balance algorithms, documented assumptions and validation procedures [58–61]. More broadly, simulation-based design depends on careful model construction, interoperability and the explicit treatment of schedules, internal gains and HVAC controls [62–67]. Advanced BIM-integrated approaches have also demonstrated the potential for improving HVAC energy performance through simulation-based optimisation and mathematical modelling techniques [68].

Validation is essential when simulations are used to support design or policy decisions. ASHRAE Guideline 14 provides statistical procedures for comparing simulated and measured energy use, including RMSE and CV(RMSE), and normalised mean bias error (NMBE), and defines the commonly applied monthly acceptance thresholds of CV(RMSE) $\leq$ 15% and NMBE $\leq \pm$5% for a model to be described as calibrated against measured monthly billing data, while calibration studies highlight the importance of monthly data, measured bills and transparent uncertainty reporting [35,69,70]. Elnabawi and Hamza (2019) [65] investigated BIM-to-building-energy-simulation interoperability and reported that DesignBuilder produced results close to actual measured residential electricity consumption, supporting its use where inputs are well documented. As discussed in Section 3.4, the present base-case model reproduces the published reference simulation extremely closely; the model is additionally checked against the three individually metered houses reported by Elnabawi (2021) [9], and the resulting monthly CV(RMSE)/NMBE values are reported and interpreted explicitly against these ASHRAE Guideline 14 thresholds rather than described simply as "validated".

3. Materials and Methods

This study applies a dynamic building-energy simulation workflow to evaluate the effect of a controlled night-ventilation mixed-mode strategy on the electricity consumption and indoor thermal conditions of a representative Bahraini residential building. The methodological sequence follows the logic commonly used in arid-climate residential simulation studies: first, the modelling tool and weather/location inputs are defined; second, the base building and operating assumptions are established; third, the tested scenario configuration is prepared; and fourth, the model is checked against measured and published data using explicit statistical acceptance criteria, and assessed using annual, monthly and hourly performance indicators [9,13].

The study intentionally uses a focused two-scenario design. Scenario S0 represents the checked closed-window base case, while Scenario S1 adds a controlled night-ventilation sequence without changing the building envelope, roof assembly, glazing, occupancy, internal gains or air-conditioning setpoint. This structure isolates the operational contribution of night ventilation and avoids conflating the results with envelope-code, cool-roof or retrofit interventions previously investigated for similar Gulf residential buildings [9]. Figure 1 presents the residential reference unit and the corresponding DesignBuilder (v2025.1) model, while Figure 2 summarises the complete methodological sequence from published case-study data to validation, controlled mixed-mode simulation and interpretation.

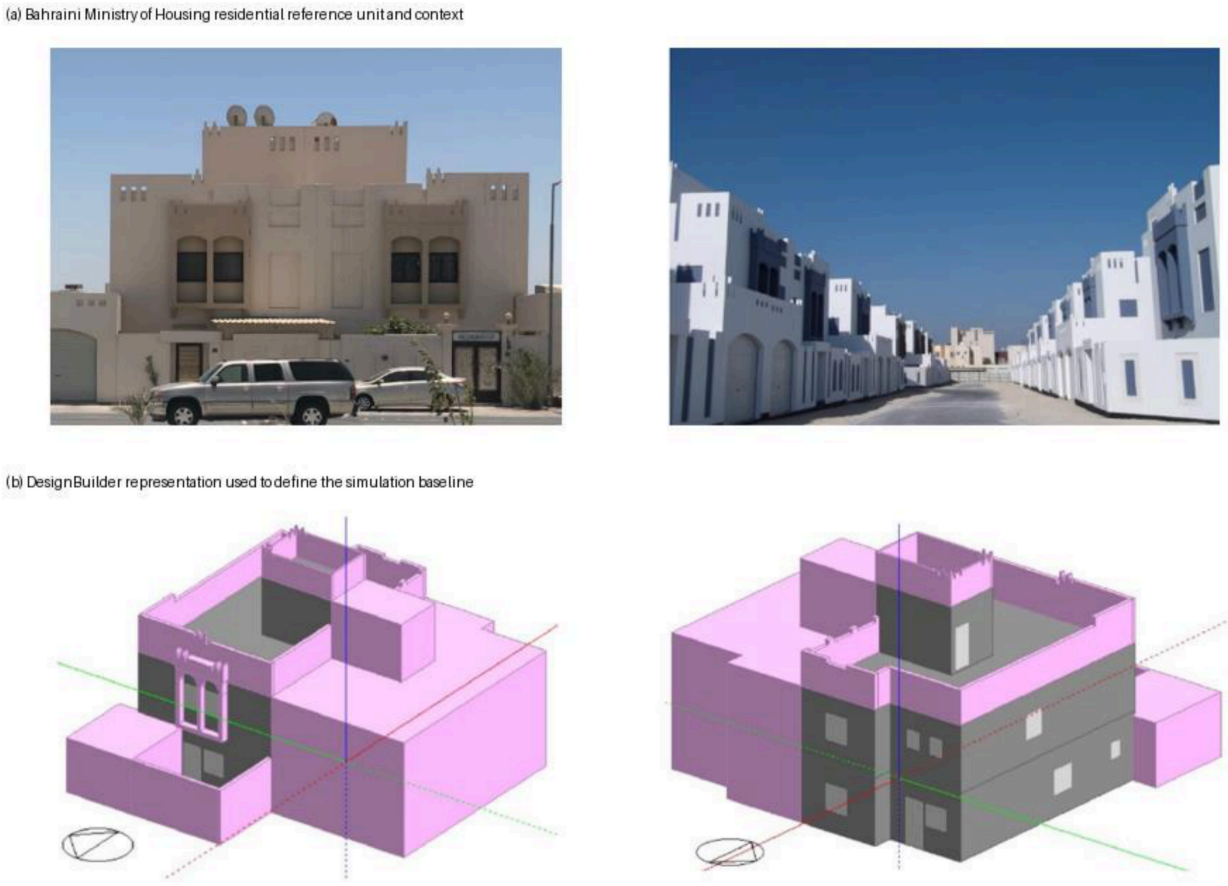


Figure 1. Bahraini Ministry of Housing residential reference unit and DesignBuilder v2025.1 representation used to define the simulation base model. Source: adapted from the published Bahraini residential case-study model [9].

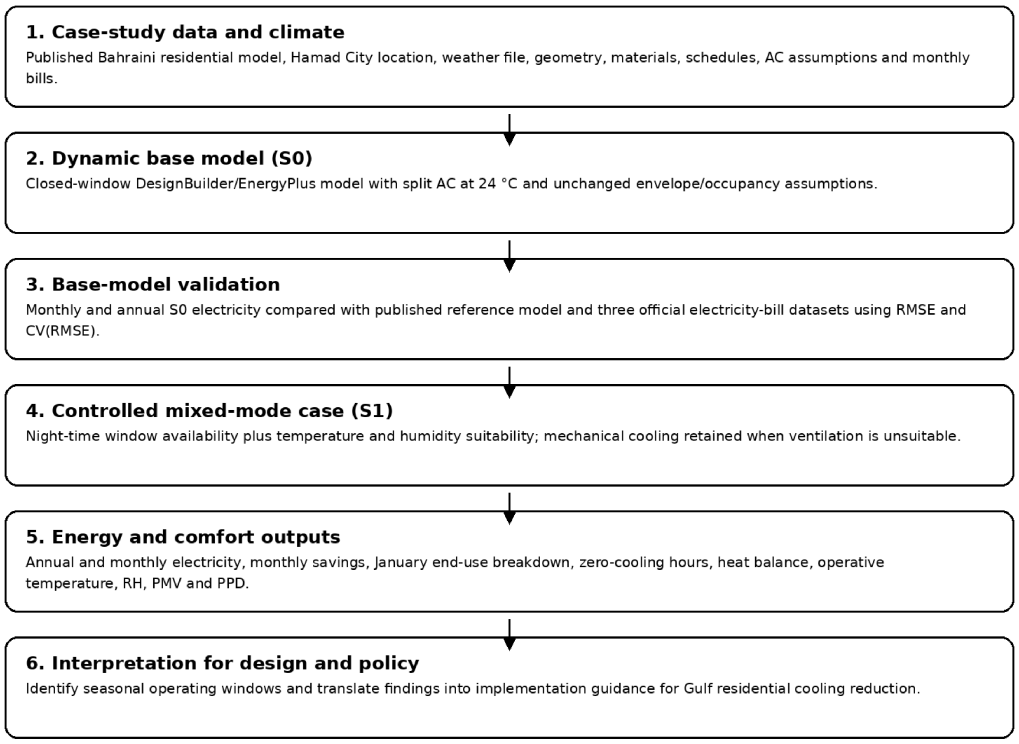


Figure 2. Methodological workflow for the controlled night-ventilation mixed-mode study.

3.1. Dynamic Energy Modelling Setup and Choice of Software

Dynamic energy simulation was selected because the research question depends on hourly interactions among climate, occupancy, internal gains, window operation and mechanical cooling. A static or steady-state method would not be able to represent the time-dependent switch between natural ventilation and split air-conditioning during the night. DesignBuilder v2025.1/EnergyPlus was therefore used as the simulation environment. DesignBuilder v2025.1 is a graphical user interface for the EnergyPlus v2023.1 calculation engine and has been used in previous arid-climate studies to model residential energy demand, building-code scenarios, roof-retrofit options and hybrid ventilation strategies [13,16,71].

The modelling workflow followed the sequence required for reliable building-energy modelling: the project location and weather file were assigned; the simplified building geometry was developed; constructions, glazing, occupancy and internal-load profiles were defined; the split air-conditioning system and thermostat setting were entered; the base model was checked against available electricity-consumption data; and then the controlled ventilation scenario was simulated. This sequence is consistent with the building-energy modelling logic described by Maile et al. (2007) [67], where model reliability depends on a transparent definition of geometry, thermal zones, schedules, systems and calibration data before testing alternative scenarios.

3.2. Building Model and Climate: The Base Case

The case-study basis is a Ministry of Housing residential unit in Hamad City, northern Bahrain, located at approximately 26.07° N and 50.30° E. Bahrain is classified as a hot–arid/hot desert climate under the Köppen–Geiger classification system and has long hot summers and milder winter periods [9,72]. This climate context is central to the present study because controlled night ventilation is expected to be seasonally selective: it may be useful during cooler winter or transition months but limited during the peak cooling season when night-time outdoor air may remain too warm or humid.

The availability of the published Bahraini residential dataset was a major reason for selecting this case. The dataset includes building geometry, construction properties, operational schedules, HVAC assumptions and monthly electricity-consumption benchmarks. This supports a more realistic simulation than a generic residential archetype because the base model can be compared with published and measured electricity data before the mixed-mode scenario is evaluated. The reference model is a two-storey dwelling with a total floor area of approximately 209 m^2. The main construction consists of a reinforced concrete frame and brick infill walls, with double-coated glazing and split air-conditioning units. Table 1 lists the principal building and system inputs retained in both S0 and S1. The only intentional difference between the two scenarios is the S1 night-ventilation control logic.

The envelope, glazing and window-to-wall-ratio (WWR) inputs listed in Table 1 are taken directly, unmodified, from the published and independently validated Bahraini Ministry of Housing case-study model of Elnabawi (2021) [9], which was itself developed from as-built drawings and a site survey of the standard Ministry of Housing typology. The external wall U-value (2.746 $W/m^2 \cdot K$) and roof U-value (0.53 $W/m^2 \cdot K$) retained here are consistent with uninsulated or lightly insulated GCC residential stock predating more recent energy-code tightening, and are broadly in the range reported for existing (pre-retrofit) Gulf housing stock in the wider regional literature [6–9]. The 24.6% WWR and 104.03 m^2 external opening area also fall within the range commonly reported for GCC standard-typology housing (approximately 15–30% WWR), and were retained unmodified from the source model specifically so that the present study's S0–S1 comparison isolates

the operational effect of night ventilation from any confounding envelope change. No independent audit of a wider Bahraini housing sample was conducted as part of the present study, and Section 6 (Limitations) states explicitly that recommendations arising from these envelope assumptions apply to this specific building configuration and should not be read as generalised to the full diversity of Bahraini residential stock without further testing across additional typologies and envelope specifications.

Table 1. Main building, envelope and system inputs retained from the published Bahraini residential model.

Parameter	Value Retained in the Present Model	Source/Notes
Building type	Two-storey Bahraini Ministry of Housing residential unit	Published residential case-study typology
Location	Hamad City, Bahrain, approximately 26.07° N, 50.30° E	Climate and weather-file basis
Climate classification	Hot–arid/hot desert climate (BWh; ASHRAE hot climate classification)	Bahrain has long hot summers and milder winters
Total floor area	209 m^2	Published model input
Floor height	3.17 m	Published model input
Ground level	0.45 m	Published model input
External wall area	421.6 m^2	Published model input
External opening area	104.03 m^2	Published model input
External wall thermal transmittance	U = 2.746 W/m^2·K	As-built envelope assumption
Roof thermal transmittance	U = 0.53 W/m^2·K	As-built roof assumption
Glazing	Double-coated 6/8/6 glazing; SHGC = 0.31; U = 3.26 W/m^2·K	Published glazing assumption
Window-to-wall ratio	24.6%	Published model input
Shading	Internal blinds with high-reflectivity slats	Published model input
Occupancy	6 occupants	Residential occupancy assumption
Lighting density	5 W/m^2 during operational hours	Published operating assumption
HVAC system	Split air-conditioning units; no heating system	Published base-model assumption
Cooling thermostat	24 °C	Used for S0 and retained when S1 is in mechanical mode
Cooling system seasonal COP	2.5	Published system assumption

3.3. Scenario Preparation for Controlled Night Ventilation

The scenario preparation in this study uses a focused operational comparison rather than a broad parametric envelope database. The base case (S0) represents conventional closed-window operation with split air-conditioning at a 24 °C cooling setpoint. The mixed-mode case (S1) retains all base-model physical and operational assumptions, including geometry, construction, occupancy, internal gains, system type, and cooling setpoint, but introduces controlled night ventilation. The purpose is to isolate the effect of an operational ventilation strategy on electricity use and indoor thermal conditions without introducing additional changes to the envelope, roof, or HVAC efficiency. The two simulated scenarios are summarised in Table 2.

Table 2. Two-scenario simulation matrix.

Scenario	Description	Purpose
S0: closed-window base case	As-built residential model; windows closed; split air-conditioning at 24 °C; no heating system.	Validation baseline and reference case for all comparisons.
S1: controlled night-ventilation mixed-mode case	Same geometry, envelope, internal loads, occupancy and AC setpoint as S0. External windows are available only during night-time periods and only when outdoor conditions satisfy thermal and humidity suitability checks.	Tests the operational impact of controlled night ventilation while avoiding confounding envelope, roof or HVAC-efficiency changes.

The S1 strategy was modelled as a controlled mixed-mode operation, not as a permanently open-window or fully naturally ventilated case. Natural ventilation was scheduled to be available during the night-time period from 19:00 to 07:00, when outdoor conditions are more likely to support passive cooling. During this availability period, outdoor air is used only when the control conditions indicate that ventilation is beneficial. If the suitability criteria are not met, the windows remain closed and mechanical cooling remains available at the 24 °C thermostat setpoint. This approach is consistent with mixed-mode ventilation theory, where natural ventilation and mechanical cooling operate as complementary systems rather than as mutually exclusive alternatives [13,27,28,34].

Figure 3 illustrates the control logic used to interpret the S1 scenario. The figure clarifies that S1 is not a simple fixed window-opening schedule. Instead, the night-time availability period is filtered by thermal suitability, enthalpy-based humidity suitability, rain closure, and wind-speed safety restrictions. This distinction is important in Bahrain because night-time outdoor air may be cooler than indoor air but may still carry a latent-load penalty. Therefore, the S1 strategy is intended to represent controlled night-purge ventilation under suitable conditions rather than uncontrolled night-time window opening.

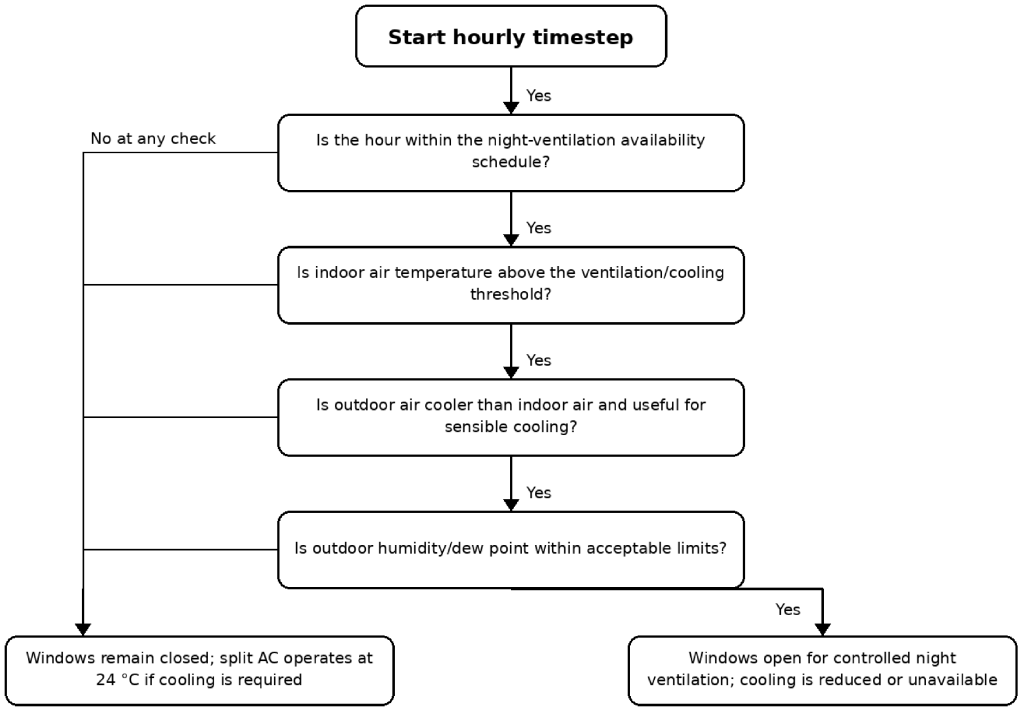


Figure 3. Hourly control logic for the S1 controlled night-ventilation mixed-mode scenario.

It is important to state explicitly what kind of intervention S1 represents. As configured (Table 3), S1 is an automated mixed-mode control sequence: it requires continuous sensing of outdoor dry-bulb temperature, outdoor enthalpy, rainfall and wind speed, and an actuation mechanism capable of opening and closing windows (or motorised vents) in response to these inputs every hour, rather than an instruction that an occupant could realistically follow by eye during the night. This distinction matters because the current Bahraini Ministry of Housing residential stock, including the reference building modelled here, does not have this sensing and actuation infrastructure installed as standard, and the manuscript does not assess the market penetration, capital cost, maintenance burden or occupant acceptance of such automated systems in Bahrain. Two implementation pathways therefore follow from the results. First, if the intent is a fully automated control solution, it would require a hardware investment (sensors, actuators, and a control unit) whose feasibility depends on a cost analysis that is outside the scope of the present energy simulation (see the indicative economic discussion in Section 5.4). Second, a lower-cost alternative is a simplified manual guideline that occupants could follow without automation—for example, "open bedroom and living-area windows on winter and shoulder-season nights (typically January, February, March, and December in Bahrain) when it is not raining and winds are calm, and keep them closed during the hot season"—recognising that a simplified manual rule of this kind would likely capture only part of the S1 savings reported here, because it cannot track the enthalpy-based humidity threshold on an hourly basis. Both pathways, and the trade-off between them, are discussed further in Sections 5.4 and 6.

Table 3. DesignBuilder control settings for the S1 controlled night-ventilation scenario.

Parameter	Model Setting	Interpretation
Natural ventilation	On	Enables outdoor-air ventilation in the S1 scenario.
Outdoor air definition	By zone	Ventilation input is assigned at the zone level.
Nominal outdoor-air rate	5 ach	Represents the available ventilation rate during permitted operation.
Operation schedule	19:00–07:00	Restricts ventilation availability to the night-time period.
General minimum outdoor temperature	−100 °C	Non-restrictive lower temperature limit.
General maximum outdoor temperature	100 °C	Non-restrictive upper temperature limit.
Mixed-mode maximum outdoor temperature	26 °C	Prevents ventilation when outdoor air is too warm for passive cooling.
Minimum outdoor enthalpy	20,000 J/kg	Lower enthalpy control threshold.
Maximum outdoor enthalpy	30,000 J/kg	Upper enthalpy control threshold to reduce humidity and latent-load risk.
Close windows when raining	Yes	Prevents ventilation during rain.
Maximum wind speed	40 m/s	Provides a high-wind safety restriction.
Mechanical cooling	Available at 24 °C	Maintains comfort when natural ventilation is unsuitable.

In DesignBuilder, natural ventilation was activated at the zone level, with outdoor air defined by the zone and a nominal available ventilation rate of 5 ach during permitted operation. The general outdoor-temperature limits were left non-restrictive by assigning a minimum outdoor temperature of −100 °C and a maximum outdoor temperature of 100 °C.

The actual restriction was applied through the mixed-mode control layer, which limited ventilation to periods when the outdoor air was suitable for passive cooling. This included a maximum outdoor temperature of 26 °C and outdoor enthalpy limits of 20,000–30,000 J/kg. Rain closure was also activated, and a maximum wind-speed limit of 40 m/s was applied as a safety restriction. The main S1 control settings are summarised in Table 3.

Accordingly, S1 should be interpreted as a temperature- and enthalpy-controlled mixed-mode strategy. Outdoor air is used only when the night-time schedule and environmental suitability limits are simultaneously satisfied, while mechanical cooling remains available whenever natural ventilation is unsuitable. This control logic follows the principle of night-purge ventilation in hot–arid climates, where daytime window opening may increase indoor heat gains, but night-time ventilation can help remove accumulated heat when outdoor conditions are favourable [33]. It is also consistent with hybrid-ventilation approaches in arid climates, where the system switches between natural and mechanical modes to reduce energy use without compromising indoor comfort [13,34].

For interpretation of the results, it is important to distinguish between zero cooling electricity and confirmed active ventilation. A zero-cooling hour indicates that mechanical cooling was not required by the model during that hour. However, unless the window-opening factor and natural-ventilation air-change-rate outputs are exported, zero cooling should not be interpreted as direct proof that the windows were open. Accordingly, throughout this manuscript the reported savings are described as the potential advantage of the control technique under the modelled suitability conditions, rather than as confirmed, field-verified cross-ventilation performance. Therefore, the hourly results are used to identify periods when mechanical cooling can potentially be reduced or avoided, while comfort interpretation is supported by operative temperature, relative humidity, and PMV/PPD outputs.

3.4. Base-Model Cross-Checked Dataset and Calculation Procedure

The cross-check approach follows the published Bahraini residential case-study workflow. Energy consumption in similar residential units can vary because of household size, occupant behaviour, appliance use, thermostat preferences and daily routines. For this reason, the original Bahraini model was validated against three official monthly electricity-bill datasets for the same residential building type. The published DesignBuilder reference simulation predicted 34,720.19 kWh/year, while the measured annual values for Houses 1–3 were 31,403, 31,760 and 39,420 kWh/year, respectively. The reported RMSE values were 6.80%, 5.23% and 8.89% for Houses 1–3, which were within the ±20% tolerance criterion adopted in the original validation [9].

In the present study, the cross-check was conducted in two steps and is reported at two levels of resolution. First, the replicated S0 model was compared with the published reference model to confirm that the same monthly and annual electricity pattern was reproduced (Section 4.1: annual difference of 0.027%, monthly CV(RMSE) of 0.41%, which comfortably meets the ASHRAE Guideline 14 monthly acceptance threshold of CV(RMSE) $\leq$ 15% for this comparison). This first step demonstrates that the present S0 model correctly reproduces the previously published simulation and is a necessary, but not sufficient, condition for describing the base case as calibrated against real building performance.

Second, the replicated S0 model was compared against each of the three individually metered houses using the standard ASHRAE Guideline 14 monthly statistics: RMSE (Equation (1)), CV(RMSE) (Equation (2)), and the normalised mean bias error, NMBE (Equation (3), added below). The results are reported in Table 4a. For House 1, CV(RMSE) = 25.9% and NMBE = +10.6%; for House 2, CV(RMSE) = 19.6% and NMBE = +9.3%; and for House 3, CV(RMSE) = 27.1% and NMBE = −11.9%. None of

the three comparisons meets the ASHRAE Guideline 14 monthly acceptance criteria of CV(RMSE) $\leq$ 15% and NMBE $\leq \pm$5% that are conventionally used to describe a model as calibrated against metered building performance. This is expected and explainable: the three houses differ from one another in annual consumption by as much as 25.5% (31,403 vs. 39,420 kWh/year) purely because of household size, occupant behaviour, appliance use, and thermostat preferences, so no single deterministic model—including the original published reference model—can be expected to track any one individual household's monthly bills within the $\pm$15%/$\pm$5% envelope. The role of the three-house comparison in this study is therefore to confirm that the replicated S0 model falls within the observed range and follows the same seasonal shape as the measured houses (Figure 3), not to claim formal calibration against any single metered building.

Table 4. Monthly electricity-consumption dataset used for base-model validation and replication check. (**a**) Monthly cross-check statistics: replicated S0 model vs. three metered houses.

Month	House 1 Measured (kWh)	House 2 Measured (kWh)	House 3 Measured (kWh)	Published Reference Model (kWh)	Replicated S0 Model (kWh)
January	1004	1300	2500	924.2781	922.027
February	882	1400	2000	1000.9700	997.8226
March	1112	1730	2600	1574.2550	1588.3140
April	1881	2354	2100	2301.1430	2304.7510
May	2892	2640	3140	3578.9480	3555.2660
June	3390	3636	2960	3964.3650	3984.6540
July	3703	4000	4110	4782.9670	4779.2880
August	3888	4280	5440	4792.6950	4801.5950
September	4158	4000	5910	4547.1540	4544.3750
October	3257	2920	4100	3759.5760	3742.6980
November	2618	2000	2350	2212.8100	2220.8530
December	2618	1500	2210	1281.0300	1287.8200
Annual total	31,403	31,760	39,420	34,720.1911	34,729.4636

(**a**)

Comparison	Mean Measured (kWh/mo)	RMSE (kWh)	CV(RMSE) (%)	NMBE (%)	Meets ASHRAE Gdl. 14 ($\leq$15%/$\pm$5%)?
S0 vs. House 1	2616.9	678.6	25.9	+10.6	No
S0 vs. House 2	2646.7	519.0	19.6	+9.3	No
S0 vs. House 3	3285.0	889.6	27.1	−11.9	No
S0 vs. published reference model	2893.3	11.9	0.41	+0.03	Yes

The word 'validated' is avoided in this manuscript wherever it would imply calibration against individual metered buildings. Instead, more precise language is used throughout: the base case is described as having been 'checked' or 'cross-checked' against the published reference model (which it is closely reproduces) and 'compared against the observed range' of the three metered houses (to which it is not formally calibrated in the ASHRAE Guideline 14 sense). This is a more accurate and defensible characterisation of what the base-case comparison demonstrates.

Root Mean Square Error (RMSE) is calculated as shown in Equation (1); Coefficient of Variation in RMSE as shown in Equation (2); and Normalised Mean Bias Error (NMBE) as shown in Equation (3). Root Mean Square Error (RMSE):

$$MSE = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \hat{x}_i)^2}{N}} \quad (1)$$

Coefficient of Variation in the Root Mean Square Error:

$$CV(RMSE) = \frac{RMSE}{\overline{x}} \times 100 \quad (2)$$

$$NMBE = [\Sigma(x_i - \hat{x}_i)/N]/\overline{x} \times 100 \quad (3)$$

where x_i is the measured value, $\hat{x}_i$ is the simulated value, N is the number of monthly data points, and $\overline{x}$ is the mean of the measured values. These equations are appropriate for the validation procedure described in the Materials and Methods Section 3.

3.5. Performance Indicators and Analysis Sequence

After the base model was checked, S1 was compared with S0 using annual, monthly and hourly indicators. The annual comparison quantified the total electricity reduction, while the monthly analysis identified the months in which controlled night ventilation was effective. Because annual indicators can hide seasonal behaviour in hot climates, the analysis then focused on January as a representative cooler month with high ventilation potential. The hourly January outputs were used to examine cooling-off hours, end-use electricity, internal heat-balance behaviour and comfort indicators. This time-sensitive analysis is consistent with the hybrid-ventilation literature showing that mixed-mode strategies in arid climates usually perform better during cooler seasons than during peak summer [13,34].

Table 5 summarises the performance indicators used in the study. The final interpretation combines energy and comfort evidence. A reduction in cooling electricity alone is not sufficient to define a successful mixed-mode strategy in Bahrain, because night ventilation may also influence relative humidity and latent load. Therefore, operative temperature, relative humidity, PMV and PPD were included in the assessment, and the final discussion interprets the results as a controlled, humidity-aware operational strategy rather than a general recommendation for uncontrolled night-time window opening.

Table 5. Performance indicators used to evaluate S0 and S1.

Indicator	Unit	Comparison/Output Basis	Purpose
Annual electricity consumption	kWh/year	S0, S1	Quantifies annual effect of controlled night ventilation.
Monthly electricity consumption	kWh/month	S0, S1	Identifies seasonal months when S1 is effective or inactive.
Absolute and percentage saving	kWh and %	S0−S1	Measures operational reduction relative to the validated base case.
Monthly contribution to annual saving	%	Monthly saving/annual saving	Shows whether savings are concentrated in cooler months.
January end-use electricity	kWh and %	Hourly S1 end uses	Explains the end-use balance behind January mixed-mode operation.

Table 5. *Cont.*

Indicator	Unit	Comparison/Output Basis	Purpose
Zero-cooling hours	hours and %	Hourly S1 cooling electricity	Identifies periods when mechanical cooling is not required.
Hourly heat-balance components	kW	EnergyPlus hourly outputs	Explains the relationship between occupancy, lighting, solar gains and sensible cooling.
Thermal-comfort indicators	°C, %, PMV, PPD	Operative temperature, RH, PMV/PPD	Checks whether energy reduction is achieved without unacceptable thermal conditions.

4. Results

4.1. Base-Case Replication and Cross-Check

Table 6 presents the monthly measured-bill data, the published reference model, the replicated S0 model and the S1 case. The replicated S0 base case produced 34,729.46 kWh/year, compared with 34,720.19 kWh/year in the published reference model. The annual difference is only 9.27 kWh/year, equivalent to 0.027% of the reference value. The monthly RMSE between S0 and the published reference is 11.88 kWh, corresponding to a CV(RMSE) of 0.41%. This confirms that the present base case closely reproduces the published model before applying the S1 control change. As reported in Table 4a and Section 3.4, however, when the replicated S0 model is instead compared against the three individually metered houses, monthly CV(RMSE) values of 25.9%, 19.6% and 27.1% and NMBE values of +10.6%, +9.3% and −11.9% are obtained—all outside the ASHRAE Guideline 14 acceptance envelope (CV(RMSE) $\leq$ 15%, NMBE $\leq \pm$5%). The model is therefore best described as closely reproducing the published reference simulation and falling within the observed range of measured Bahraini houses of this type, rather than as being formally calibrated against any individual metered building.

Table 6. Monthly electricity validation and S1 comparison (kWh).

Month	House 1 Bill	House 2 Bill	House 3 Bill	Replicated S0	Published Reference	S1 Mixed Mode
January	1004	1300	2500	922.0	924.3	690.3
February	882	1400	2000	997.8	1001.0	686.6
March	1112	1730	2600	1588.3	1574.3	1332.4
April	1881	2354	2100	2304.8	2301.1	2291.4
May	2892	2640	3140	3555.3	3578.9	3555.3
June	3390	3636	2960	3984.7	3964.4	3984.7
July	3703	4000	4110	4779.3	4783.0	4779.3
August	3888	4280	5440	4801.6	4792.7	4801.6
September	4158	4000	5910	4544.4	4547.2	4544.4
October	3257	2920	4100	3742.7	3759.6	3743.0
November	2618	2000	2350	2220.9	2212.8	2190.8
December	2618	1500	2210	1287.8	1281.0	993.3
Annual total	31,403	31,760	39,420	34,729.5	34,720.2	33,593.0

Figure 4 visualises the same validation comparison. The three measured houses show a consistent seasonal pattern: consumption rises sharply from late spring, remains high during the hot months and declines in winter. The variation among the three houses is ex-

pected because residential electricity use is affected by household size, lifestyle, thermostat behaviour, appliance use and occupancy schedules [18]. The replicated S0 and published reference model follow the same seasonal trend, supporting their use as the basis for the controlled-ventilation comparison.

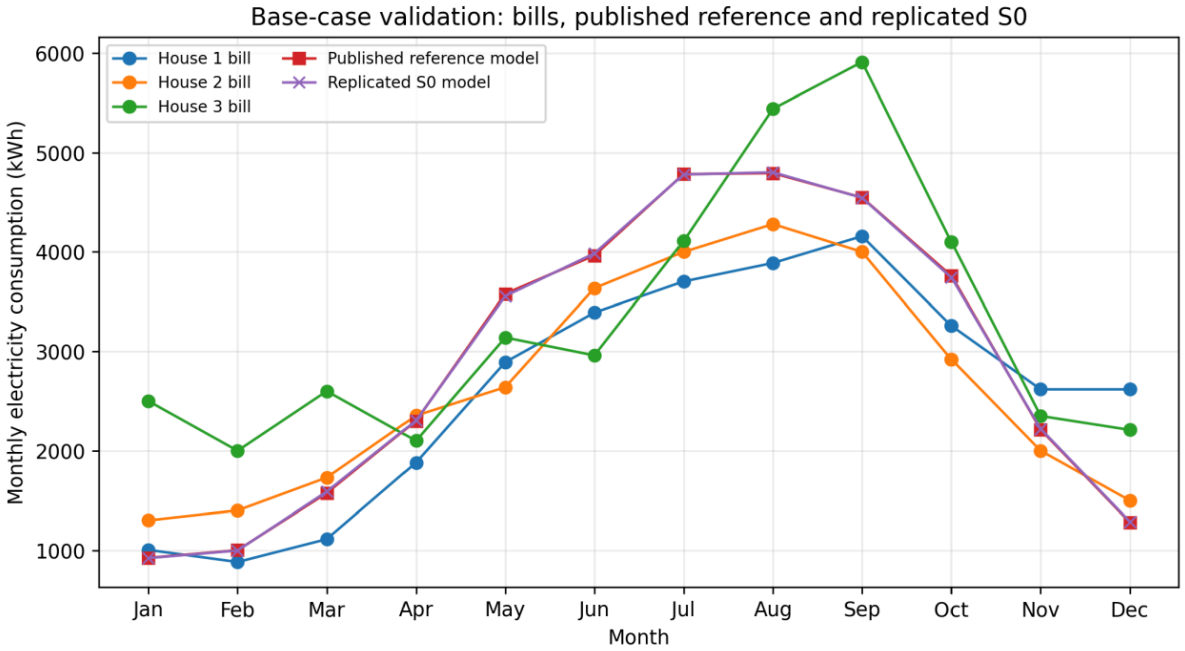


Figure 4. Monthly validation comparison among official bills, the published reference model and the replicated S0 base case.

4.2. Monthly and Annual Energy Impact of Controlled Night Ventilation

Figure 5 compares monthly electricity consumption under S0 and S1. The controlled night-ventilation case reduces annual simulated electricity consumption from 34,729.46 kWh/year to 33,593.04 kWh/year. The annual saving is 1136.42 kWh/year, equivalent to 3.27% relative to S0. This saving is smaller than physical retrofit savings reported in the Bahraini code and roof studies, but S1 is an operational strategy rather than a material retrofit [9].

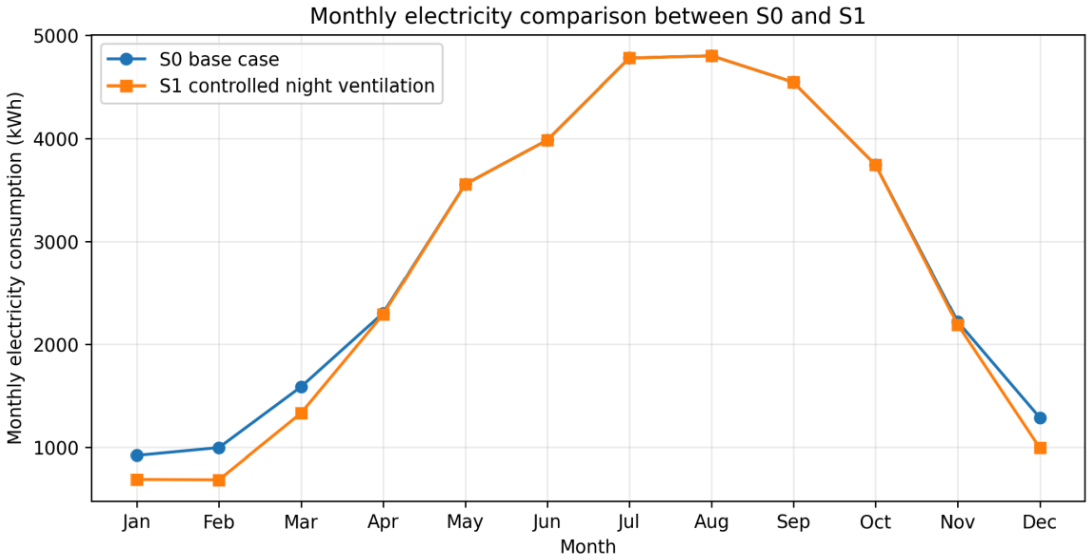


Figure 5. Monthly electricity-consumption comparison between the S0 base case and the S1 controlled night-ventilation case.

Figure 6 and Table 7 show that the saving is highly seasonal. January, February, March and December account for 96.2% of the annual saving. February gives the largest percentage reduction at 31.2%, followed by January at 25.1%, December at 22.9% and March at 16.1%. April and November produce small reductions, while May to September show no meaningful reduction. This confirms that controlled night ventilation should be presented as a winter and shoulder-season strategy for Bahrain rather than a year-round alternative to air-conditioning.

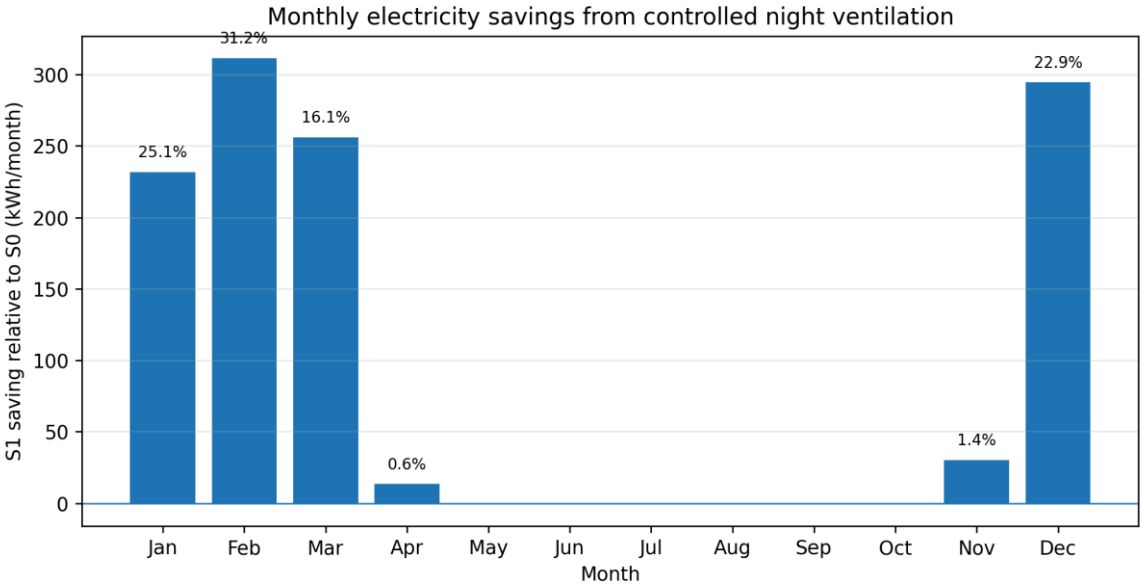


Figure 6. Monthly electricity savings from S1 relative to S0. Percentage labels show the monthly reduction relative to S0 for months with meaningful positive savings.

Table 7. Monthly S0–S1 electricity savings and contribution to annual saving.

Month	S0 (kWh)	S1 (kWh)	Saving (kWh)	Saving (%)	Share of Annual Saving (%)
January	922.0	690.3	231.7	25.1	20.4
February	997.8	686.6	311.3	31.2	27.4
March	1588.3	1332.4	255.9	16.1	22.5
April	2304.8	2291.4	13.3	0.6	1.2
May	3555.3	3555.3	−0.0	−0.0	−0.0
June	3984.7	3984.7	0.0	0.0	0.0
July	4779.3	4779.3	0.0	0.0	0.0
August	4801.6	4801.6	0.0	0.0	0.0
September	4544.4	4544.4	0.0	0.0	0.0
October	3742.7	3743.0	−0.3	−0.0	−0.0
November	2220.9	2190.8	30.0	1.4	2.6
December	1287.8	993.3	294.5	22.9	25.9
Annual total	34,729.5	33,593.0	1136.4	3.27	100.0

4.3. January Hourly Cooling Behaviour and End-Use Energy Interpretation

January was selected for hourly diagnosis because it is one of the months with the largest reduction under the S1 mixed-mode scenario and because hourly end-use and comfort outputs are available for this period.

Figure 7 compares the January end-use electricity consumption of the closed-window base case (S0) and the controlled night-ventilation mixed-mode case (S1). The comparison shows that the non-cooling end uses remain effectively unchanged between the two scenarios. Lighting electricity is approximately 354.7 kWh in both cases, and system-pump

electricity is approximately 248.3 kWh in both cases. This is expected because the S1 scenario does not modify lighting schedules, occupancy, pump assumptions, internal loads, or equipment operation. The main difference between the two cases is therefore associated with cooling electricity.

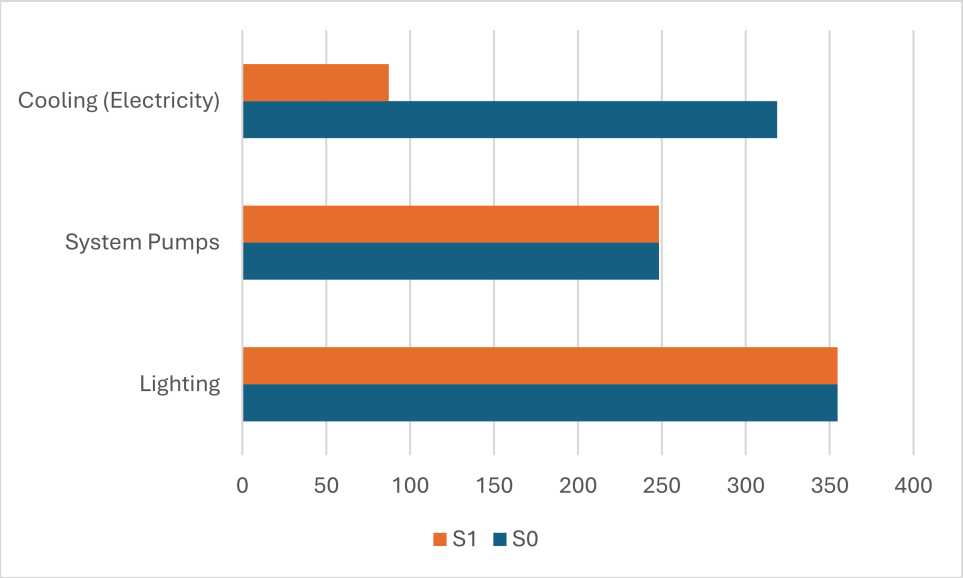


Figure 7. January end-use electricity comparison between the S0 closed-window base case and the S1 controlled night-ventilation mixed-mode case. Lighting and system-pump electricity remain effectively unchanged, while cooling electricity decreases substantially from approximately 319.0 kWh in S0 to 87.3 kWh in S1.

In the S0 base case, January cooling electricity is approximately 319.0 kWh, while in the S1 mixed-mode case it decreases to 87.3 kWh. This represents a reduction of about 231.7 kWh, equivalent to a 72.6% decrease in January cooling electricity. At the monthly total electricity level, January consumption decreases from 922.03 kWh in S0 to 690.31 kWh in S1, giving a total monthly reduction of 231.72 kWh, or approximately 25.1%. Therefore, the January saving is not caused by changes in non-cooling end uses; it is almost entirely the result of reduced cooling operation under the controlled night-ventilation strategy.

This interpretation is important because it prevents the monthly S1 value from being misread as cooling electricity alone. In S1, cooling electricity represents only 12.6% of January electricity consumption, while lighting and system pumps account for 51.4% and 36.0%, respectively. By contrast, in S0, cooling electricity represents approximately 34.6% of January electricity use. The controlled night-ventilation strategy therefore changes the structure of January electricity demand: cooling becomes a much smaller share of total consumption, while fixed or schedule-driven end uses become proportionally more dominant.

The result also shows why January is a suitable month for hourly analysis. The large reduction in cooling electricity indicates that outdoor conditions during many night-time or cooler-period hours are suitable for reducing mechanical cooling demand. It should be emphasised, however, that this reduction reflects the model's cooling-electricity response to the S1 control logic (i.e., the potential advantage of the control technique under the modelled suitability thresholds) rather than field-confirmed cross-ventilation, since the window-opening factor and natural-ventilation air-change-rate outputs were not exported in this study (see Sections 3.3 and 6). However, because lighting and pump electricity remain constant, further reductions in January electricity would require additional measures beyond ventilation, such as lighting efficiency, pump-control optimisation, or broader operational-management strategies.

Figure 8 shows the hourly cooling electricity profile. Cooling electricity is zero for 425 out of 744 h (57.1%). The maximum hourly cooling electricity is 1.74 kW, and the monthly average is 0.117 kW. Therefore, January under S1 is not a continuously cooled period; it is characterised by extended cooling-off hours interrupted by short cooling events. Figure 8 further shows that the average hourly cooling profile has its lowest value around 10:00 and its highest value around 19:00, suggesting that cooling is influenced by the combined timing of occupancy, internal gains and outdoor conditions.

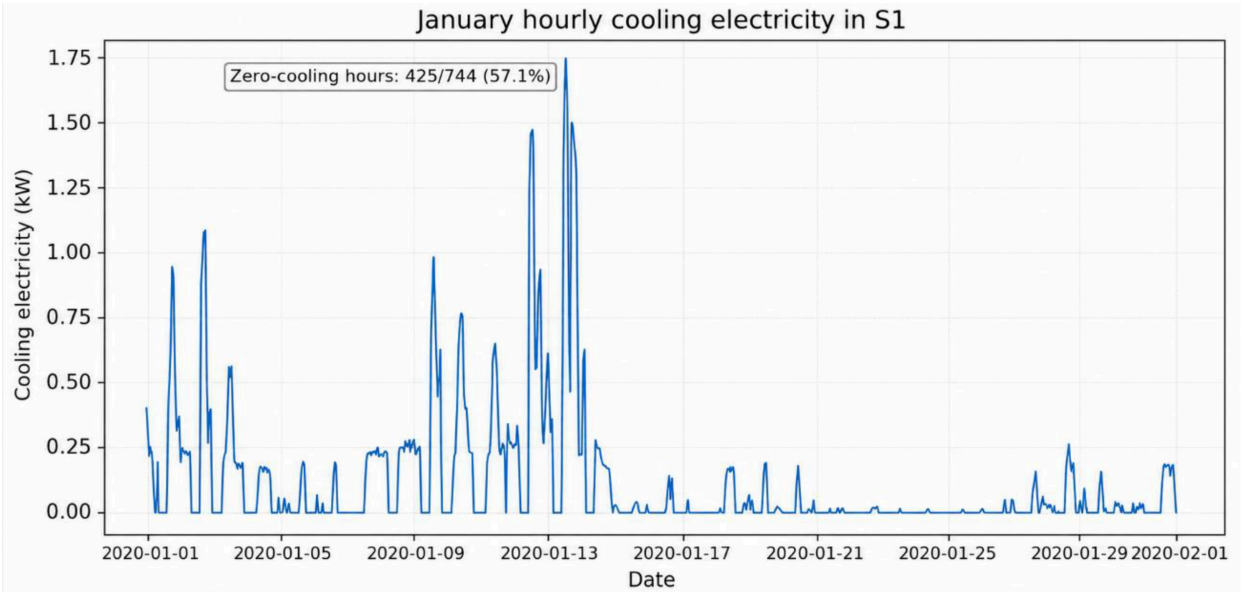


Figure 8. January hourly cooling electricity in the S1 mixed-mode scenario. The annotation indicates the share of hours with zero cooling electricity.

Figure 9 provides a heat-balance explanation for the hourly behaviour summarised in Table 6. Occupancy is the dominant internal sensible gain during scheduled occupied periods, generally reaching approximately 4–5 kW, while lighting gains are lower and solar gains through exterior windows are comparatively small in January. The zone's sensible cooling curve is intermittent and remains close to zero for many hours, which is consistent with the high number of zero-cooling hours reported in Figure 7 and Table 8.

Table 8. January hourly energy summary for S1.

January S1 Metric	Value
Total hourly records	744 h
Total S1 electricity from hourly outputs	690.4 kWh
Lighting electricity	354.7 kWh (51.4%)
System-pump electricity	248.3 kWh (36.0%)
Cooling electricity	87.3 kWh (12.6%)
Zero-cooling hours	425 h (57.1%)
Peak hourly cooling electricity	1.74 kW
Average hourly cooling electricity	0.117 kW

The lower panel of Figure 10 shows a substantial latent-load pattern during occupied periods. This matters for Bahrain because reduced sensible cooling does not automatically mean that humidity-related comfort or latent cooling loads are resolved. For this reason, the S1 strategy should be interpreted as humidity-aware mixed-mode operation, not uncontrolled night-time window opening. The final design rule should include a temperature condition and humidity or dew-point restriction before windows are opened.

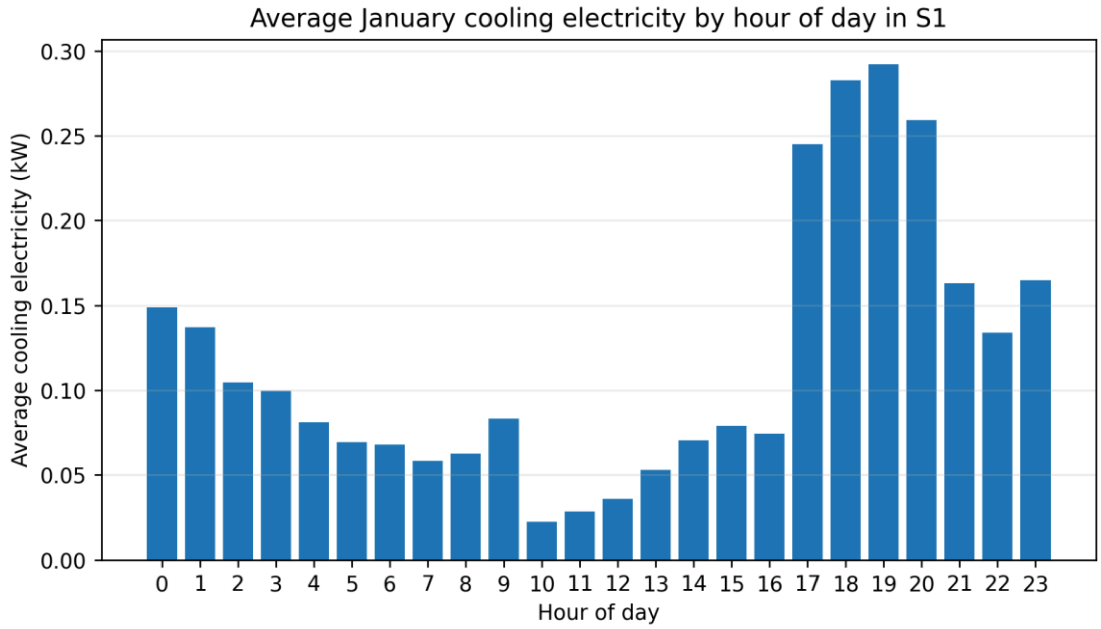


Figure 9. Average January cooling electricity by hour of day under S1.

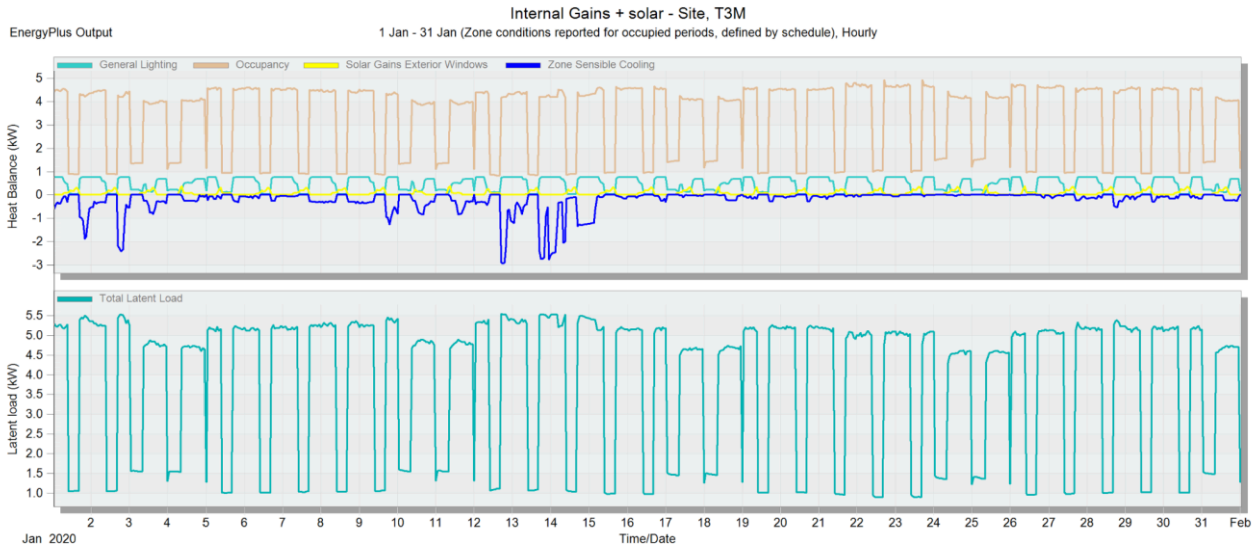


Figure 10. Hourly EnergyPlus heat-balance components for January under the S1 controlled night-ventilation mixed-mode scenario. Negative sensible cooling values indicate heat removed by the cooling system.

4.4. January Thermal Comfort and Humidity Behaviour

Figure 11 compares January hourly operative temperature with outdoor dry-bulb temperature. The mean operative temperature is 23.81 °C, with a minimum of 21.93 °C and a maximum of 25.05 °C. A simple diagnostic band of 22–27 °C is used in the figure to visualise temperature stability; 740 h (99.5%) fall within this band. This is not presented as a final adaptive-comfort criterion, but as a diagnostic indication that January indoor temperatures remain relatively stable during the mixed-mode operation. Figure 12 extends the comfort interpretation to monthly values. Indoor operative temperature remains much less variable than outdoor dry-bulb temperature, confirming the stabilising effect of the building and cooling-control sequence. However, Table 9 shows that humidity and PMV/PPD outputs require careful interpretation: mean RH is 65.4%, with a range from 28.7% to 86.9%, while only 0.5% of January hours fall within the −0.5 to +0.5 PMV band. This PMV result is an important qualification of the energy findings, and, it is now

stated plainly rather than only noted in passing on the PMV metric, the S1 January indoor environment falls outside the narrow ±0.5 'acceptable' PMV band for 99.5% of hours, with a mean PMV of +0.94 (warm side) and a mean PPD of 24%. This does not invalidate the energy result; rather, it indicates that thermal-comfort claims should be linked to the correct comfort model, clothing assumption, metabolic rate, air speed and mixed-mode control state [37,39,73] and it is addressed directly in Section 5.2.

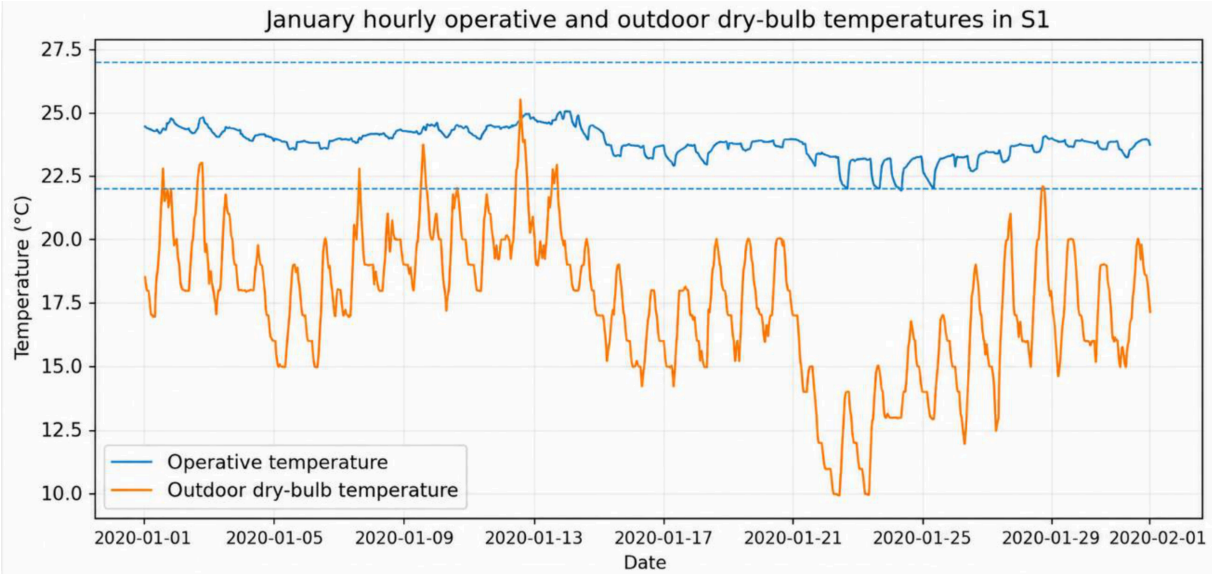


Figure 11. January hourly operative temperature and outdoor dry-bulb temperature in S1. Dashed lines indicate a simple 22–27 °C diagnostic band rather than a final adaptive-comfort criterion.

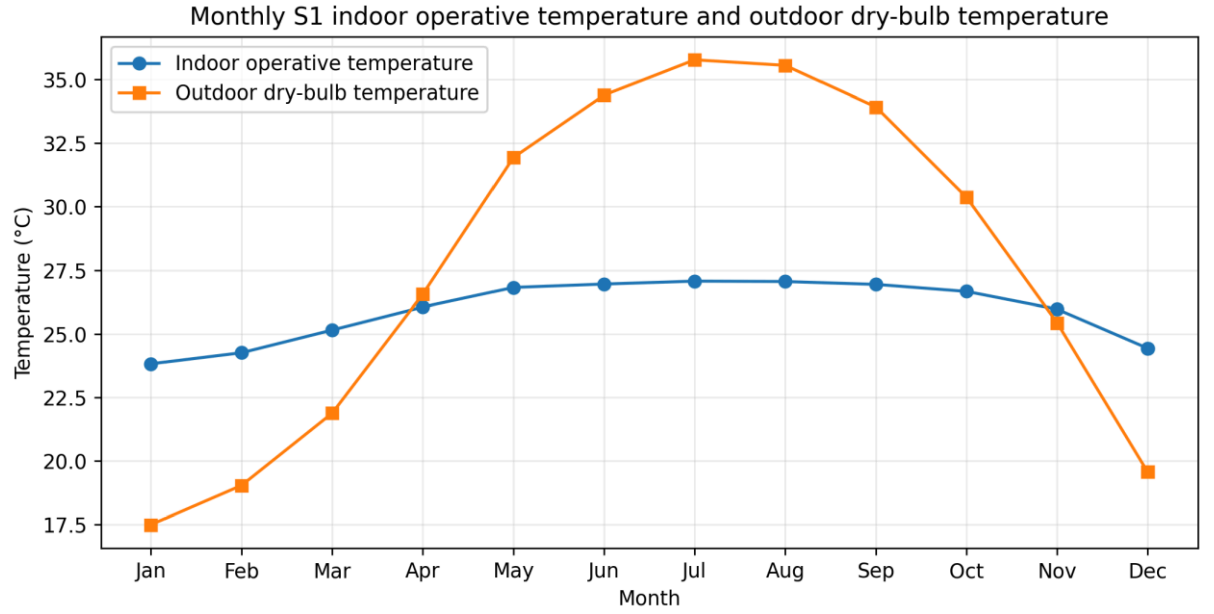


Figure 12. Monthly S1 indoor operative temperature compared with outdoor dry-bulb temperature.

Table 9. January hourly comfort and humidity summary for S1.

January Comfort/Humidity Metric	Value
Mean indoor air temperature	23.86 °C
Indoor air temperature range	21.84–25.28 °C
Mean operative temperature	23.81 °C
Operative temperature range	21.93–25.05 °C

Table 9. *Cont.*

January Comfort/Humidity Metric	Value
Hours within 22–27 °C diagnostic band	740 h (99.5%)
Mean outdoor dry-bulb temperature	17.48 °C
Outdoor dry-bulb temperature range	9.93–25.50 °C
Hours with outdoor dry-bulb below operative temperature	743 h (99.9%)
Mean relative humidity	65.4%
Relative-humidity range	28.7–86.9%
Hours with RH between 30% and 70%	495 h (66.5%)
Mean PMV/mean PPD	0.94/24.0%
Hours within −0.5 to +0.5 PMV	4 h (0.5%)
Hours with PPD below 10%	4 h (0.5%)

5. Discussion

5.1. Seasonal Value of Controlled Night Ventilation

The results show that controlled night ventilation provides a measurable but highly seasonal reduction in electricity use. The annual reduction of 3.27% is modest, but the monthly reductions in January, February, March and December are substantial. This pattern is consistent with hybrid-ventilation studies in arid climates, which report stronger performance in cooler seasons and limited benefits during hot months [13,28,34,56].

The result should therefore not be framed as a failure of night ventilation. Rather, it identifies the correct operational window. In Bahrain, controlled night ventilation is not a substitute for air-conditioning in peak summer. It is a seasonal load-management strategy that can reduce cooling operation when outdoor temperature and humidity conditions permit. This distinction is important for both design and policy because it prevents unrealistic claims and supports targeted implementation.

5.2. Energy, Comfort and Humidity Trade-Offs

The January hourly results reveal an important distinction between sensible cooling reduction and full environmental comfort. The cooling electricity profile indicates many hours with no active cooling, but the heat-balance output and humidity summary show that latent loads remain relevant. This is especially important in coastal Gulf climates, where night air may be cooler but humid. Therefore, a successful control sequence should not be based on outdoor dry-bulb temperature alone. It should include a dew-point, relative-humidity or enthalpy restriction before window opening is enabled.

The PMV/PPD results reported in Section 4.4 require direct discussion rather than a brief caveat, because they qualify the headline energy finding. Under the strict steady-state PMV/PPD metric, the S1 January indoor environment falls within the ±0.5 PMV 'acceptable' band for only 4 of 744 h (0.5%), with a mean PMV of +0.94 and mean PPD of 24%. Taken at face value, this indicates that for most January hours the space is on the warm side of the narrow PMV comfort band. Two considerations qualify this finding without dismissing it. First, PMV/PPD was developed by Fanger (1970) [36] for steady-state, fully air-conditioned environments and is known to over-predict discomfort in naturally ventilated and mixed-mode spaces, where occupants adapt behaviourally (clothing, air movement, expectation) in ways the steady-state heat-balance model does not capture [23,25,42]. Second, ASHRAE Standard 55-2023 permits the adaptive comfort model as an alternative evaluation method, but that method is formally defined for naturally conditioned spaces in which no mechanical cooling system is operating; because S1 retains mechanical cooling as a fallback whenever natural ventilation is unsuitable, S1 does not meet the strict applicability conditions for the adaptive method in every hour either,

and the present dataset does not include the additional field or survey inputs (running mean outdoor temperature series, occupant clothing and activity records) that a rigorous adaptive-model evaluation would require. For this reason, this manuscript does not claim ASHRAE 55 adaptive-model compliance for the S1 case. Instead, the conclusion is stated conservatively: the January PMV/PPD results indicate that the controlled night-ventilation strategy achieves its reported energy savings together with a measurable thermal-comfort trade-off under the PMV metric, and this trade-off should be resolved in future implementation either by tightening the control-temperature threshold (e.g., lowering the 26 °C outdoor cut-off), by adding a fan-assisted air-movement allowance recognised in ASHRAE 55, or by validating the adaptive model against field-monitored occupant data, as recommended in Section 6.

5.3. Implications for Planning Practice and Policy Integration

The findings have implications beyond the individual dwelling model. Planning practice in hot–arid cities often addresses cooling demand through urban form, shading, envelope codes and HVAC efficiency. This study indicates that residential operation should also be considered. Because the S1 benefit is concentrated in cooler months, planning policy should not treat natural ventilation as a blanket energy-efficiency measure. Instead, it should be integrated as a controlled seasonal strategy within housing design guidance, post-occupancy energy management and occupant education.

At the planning scale, controlled night ventilation can support peak-demand management and seasonal energy conservation when combined with climate-sensitive urban design. Street orientation, wind access, reduced urban heat storage, shaded outdoor spaces and lower night-time urban temperatures can improve the climatic opportunity for ventilative cooling [48,74,75]. However, the strategy should be accompanied by safeguards: noise, dust, outdoor air quality, privacy, security and humidity must be considered before natural ventilation is promoted in residential policy.

Policy integration could take three forms. First, residential energy codes could include optional mixed-mode readiness provisions, such as operable-window requirements, secure night-ventilation openings and humidity-aware control guidance. Second, government housing programmes could provide seasonal operation guidance to residents, explaining when windows should remain closed and when controlled night ventilation is useful. Third, simulation-based compliance methods could require monthly and hourly reporting for passive strategies, because annual totals alone can hide periods of usefulness or risk.

5.4. Design, Regulation, and Implementation

The implication of design is that controlled night ventilation should be designed as a system, not simply as operable windows. Table 10 translates the simulation findings into design, regulatory and implementation actions. The main requirement is control: the dwelling needs openings that can be used safely at night, a control rule that accounts for outdoor temperature and humidity, and clear occupant guidance. Without these elements, night ventilation may become either underused or misused.

Indicative economic feasibility: The 3.27% annual saving (1136.42 kWh/year) should be placed in the context of Bahrain's residential electricity tariff before being described as a practically achievable benefit. Bahrain applies a tiered, heavily subsidised residential electricity tariff for Bahraini nationals, with the lowest tier priced on the order of a few fils (hundredths of a Bahraini Dinar) per kWh; using an illustrative low-tier rate of approximately 0.02–0.03 BHD/kWh, the annual S1 saving of 1136.42 kWh corresponds to approximately 23–34 BHD (roughly USD 60–90) per year at the household level. This is a modest sum relative to the likely capital cost of an automated sensor-and-actuator

mixed-mode control system of the kind implied by Table 3, and the present study does not include a costed bill-of-materials or installation-cost estimate for such a system in the Bahraini market; a full payback-period calculation therefore cannot be responsibly presented without that costing data, and none is fabricated here. Under the current subsidised tariff, the direct household bill-saving case for a fully automated S1 system is therefore limited, and this is now stated explicitly rather than left implicit. The strategy's value case is stronger when framed around three other channels that are not directly monetised in this paper: (i) reduced peak and off-peak generation and grid-capacity requirements at the utility scale, which matter even when the household-level bill saving is small under subsidy; (ii) long-term exposure if or when subsidies are reduced, which would proportionally increase the household-level value of the same kWh saving; and (iii) the low-cost manual-guideline implementation pathway described in Section 3.3, which avoids most of the capital cost of automation and could be delivered through occupant education rather than hardware. The energy saving reported in this paper is therefore presented as indicative potential rather than a demonstrated, practically achievable household benefit, and a costed payback analysis—ideally using verified Electricity and Water Authority tariff schedules and quoted control-system installation costs—is identified as a specific priority for future work in Section 6.

Table 10. Design, regulation and implementation implications of the controlled night-ventilation results.

Scale	Recommended Action	Rationale from This Study
Building design	Provide secure, insect-screened and privacy-sensitive operable openings for night ventilation.	S1 savings occur during specific months and require windows to be safely available at night.
Mechanical systems	Use mixed-mode control that locks out window opening during hot or humid periods and retains AC at 24 °C when needed.	January results show many zero-cooling hours, but latent load remains important.
Controls and sensors	Include outdoor temperature, indoor temperature, RH/dew point and window status in the control logic.	Dry-bulb temperature alone is insufficient for coastal Bahrain.
Building regulations	Allow optional mixed-mode readiness credits in residential codes while requiring humidity-aware safeguards.	The strategy is low-cost but seasonal, so it should complement rather than replace envelope and HVAC regulations.
Planning policy	Combine dwelling-level controls with urban heat mitigation, shading and wind-path planning.	Cooler night-time urban conditions can increase the useful window for ventilative cooling.
Occupant guidance	Provide simple seasonal instructions: use controlled night ventilation mainly in winter/shoulder months and avoid humid/hot nights.	January, February, March and December provide 96.2% of annual S1 savings.

For implementation, controlled night ventilation should be considered a complementary measure alongside stronger strategies such as envelope improvement, efficient cooling equipment, roof reflectance and demand-side management. Elnabawi (2021) [9] shows that envelope-code and roof strategies can produce larger cooling savings than the S1 operational strategy; nevertheless, controlled night ventilation has the advantage of potentially being implemented through operation, controls and occupant guidance with minimal physical retrofit. The most robust policy pathway is therefore integration, not substitution: codes and retrofit programmes should combine physical efficiency measures with controlled seasonal operation.

5.5. Policy Priority Ordering Relative to Other Interventions

Controlled night ventilation should be positioned relative to other, larger-impact interventions for Bahraini residential cooling. Elnabawi (2021) [9] reports that envelope-code compliance and roof-reflectance retrofits in the same Bahraini residential context can achieve cooling-related savings well in excess of the 3.27% annual reduction found here for S1, and that residential air-conditioning can account for approximately 80% of peak residential electricity demand in Bahrain. Read together with the present results—in which S1 delivers zero meaningful saving between May and September, the period in which Bahraini peak electricity demand actually occurs—controlled night ventilation makes no contribution to summer peak-load reduction and should not be promoted as a standalone residential energy-efficiency measure or as a substitute for envelope and HVAC-efficiency investment.

A more defensible policy priority order, consistent with the evidence in this study and in Elnabawi (2021) [9], is: (1) envelope performance upgrades (wall and roof insulation, improved glazing), which reduce cooling load across the whole year including the peak summer season; (2) HVAC-efficiency improvements (higher-COP equipment, correct sizing and maintenance), which reduce electricity use whenever mechanical cooling operates; (3) roof-reflectance and cool-roof retrofits, which specifically target solar heat gain during the hottest months; and only then (4) controlled night ventilation and other operational/behavioural strategies, positioned as a low-cost, no-retrofit complement that captures additional savings specifically in the cooler shoulder months (January, February, March, December) where envelope and HVAC measures alone leave residual, avoidable cooling electricity. Framed this way, controlled night ventilation is a legitimate but secondary tool in the Bahraini residential policy mix: valuable because it requires no capital-intensive retrofit and can be deployed through guidance and, optionally, low-cost controls, but not a substitute for the higher-impact, peak-load-relevant measures that should be prioritised first.

6. Limitations and Future Work

This study is intentionally focused on two scenarios. This strengthens attribution of the S1 effect but also limits generalisation. Future work should test multiple climate years, orientations, window-opening areas, occupancy profiles, thermostat settings, humidity-control thresholds and residential typologies. The analysis should also export the window-opening factor, natural-ventilation air-change rate, outdoor dew point, indoor air speed and CO_2 concentration to confirm when zero-cooling hours coincide with actual window opening and acceptable indoor air quality.

Single-building, single-orientation and single-window configuration: The simulation is based on one Bahraini Ministry of Housing dwelling with one construction layout, one orientation, and a fixed window-to-wall ratio (24.6%) and external opening area (104.03 m^2) taken from the published reference model. Controlled night-ventilation performance is known from the wider literature to be sensitive to building orientation relative to prevailing winds, the distribution of openings across façades (rather than only their total area), and the degree of cross-ventilation path each layout allows [29,31]. None of these factors was varied in the present study, and the results reported here—including the 3.27% annual saving and its seasonal distribution—should therefore be read as specific to this building configuration and orientation, not as a generalised prediction for the Bahraini residential stock. This constraint is stated explicitly here, in the Discussion (Section 5.4), and in the Conclusions (Section 7), and it is the basis for the sensitivity analysis of future work items below.

Simulation-to-reality gap: Although the base case is cross-checked against published and metered monthly electricity data (Section 3.4), the present study does not, and by

its nature as a simulation study cannot, fully replicate real occupant behaviour: actual window-opening decisions, infiltration variability, occasional deviations from the assumed occupancy and thermostat schedules, and day-to-day operational choices are all simplified or held fixed in the EnergyPlus model. The reported S1 savings should accordingly be read as the expected performance of the modelled control logic under the stated assumptions, not as an assured, field-verified real-world outcome. Field monitoring in occupied Bahraini dwellings, discussed further below, is the appropriate next step to close this gap.

Cross-ventilation not directly confirmed: As already noted in Sections 3.3 and 4.3, the hourly results in this study report reduced cooling electricity and zero-cooling hours, but do not directly report the window-opening factor, ventilation airflow rate, or air-change rate, because these outputs were not exported from the EnergyPlus runs underlying this analysis. The manuscript therefore consistently frames the S1 result as the potential advantage of the control technique rather than as confirmed cross-ventilation performance, and this framing is intended to prevent readers from over-interpreting the simulation results as direct evidence of airflow.

Representativeness of the envelope assumptions: The building envelope, glazing and construction properties (Table 1) were adopted unmodified from the published Bahraini residential model of Elnabawi (2021) [9]. As discussed in Section 3.2, these properties (external wall U = 2.746 $W/m^2 \cdot K$; roof U = 0.53 $W/m^2 \cdot K$) are consistent with existing, pre-retrofit GCC residential construction rather than the tightest current energy-code targets, but no systematic comparison against current Bahraini building-code minima or a wider sample of the residential stock was performed as part of this study. This is compounded by ownership and tenancy arrangements, which shape building maintenance and occupants' practical ability to adopt operational strategies such as window ventilation [76–98]. Because envelope performance directly affects the magnitude of both the cooling load and the potential for night-purge ventilation to remove stored heat, this is a material constraint on generalizability and is listed here as a specific priority for future work.

The comfort analysis is diagnostic rather than final. Operative temperature, RH, PMV and PPD are reported, but final comfort claims should be checked against the selected comfort standard, occupant clothing and metabolic assumptions, air movement, adaptive comfort acceptability and occupied-hour definitions. As discussed in Section 5.2, the January PMV/PPD results indicate a real thermal-comfort trade-off under the strict PMV metric that this study does not resolve; field-based adaptive-comfort evaluation is required before a definitive comfort claim can be made. Future studies should also combine simulation with field monitoring or post-occupancy survey data to capture actual occupant behaviour and acceptance of night ventilation in Bahraini dwellings.

Finally, the paper evaluates one representative dwelling model. While the model is grounded in published Bahraini data, the results should not be transferred to all Bahraini housing without testing additional typologies, microclimates and household practices. Planning and regulatory use should therefore treat the results as evidence of seasonal potential, not as a universal performance guarantee.

No formal sensitivity or parametric analysis was conducted. The results reported in this paper are based on a single building model, a single typical meteorological year, a single mixed-mode control-temperature upper limit (26 °C) and a single enthalpy window (20,000–30,000 J/kg). No sensitivity sweep across these control parameters, and no parametric variation in the ventilation air-change rate, was conducted for this manuscript, and none of the design, regulatory or policy recommendations in Table 8 or Section 5.5 should be read as validated across a wider parameter space; they apply specifically to the building and control configuration modelled here. As a direct, concrete priority for future work, at least two of the following three sensitivity dimensions should be tested and reported in a

follow-up study before the recommendations are generalised: (a) ventilation air-change rates of 3, 5 and 10 ach; (b) mixed-mode control-temperature upper limits of 24, 26 and 28 °C; and (c) cooling thermostat setpoints of 23, 24 and 25 °C. This sensitivity analysis is proposed as future work.

Future studies should therefore expand the analysis in seven directions. First, DesignBuilder/EnergyPlus outputs should include the window-opening factor, natural-ventilation ACH, indoor air speed, outdoor dew point, and indoor relative humidity to confirm whether zero-cooling hours coincide with active and suitable natural ventilation. Second, the controlled night-ventilation strategy should be tested across additional Bahraini housing layouts, orientations, and occupancy patterns, explicitly including a parametric sweep of building orientation and window distribution to address the generalizability constraint identified above. Third, the study should be extended to compare temperature-only, enthalpy-based, and dew-point-based control algorithms. Fourth, field monitoring should be conducted in occupied homes to validate indoor temperature, humidity, window use, and AC operation during cooler months, which would also allow a field-based evaluation of the ASHRAE 55 adaptive comfort model that the present simulation-only dataset cannot support. Fifth, future work should combine controlled night ventilation with envelope improvement, efficient lighting, smart thermostats, and renewable-energy systems to assess whether low-cost operational strategies can complement deeper residential decarbonization measures. Sixth, the sensitivity/parametric analysis specified above (ventilation rate, control-temperature threshold and cooling setpoint) should be conducted and reported. Finally, a costed economic analysis—using verified Bahraini utility tariff schedules and quoted automated-control hardware and installation costs—should be performed to convert the indicative economic discussion in Section 5.4 into a defensible payback-period estimate.

7. Conclusions

This study examined whether a controlled night-ventilation mixed-mode strategy can reduce residential electricity consumption in Bahrain without compromising indoor thermal comfort, comparing a closed-window base case (S0), cross-checked against published and metered Bahraini electricity data, with a controlled night-ventilation scenario (S1) in which windows are available only during suitable night-time conditions.

The key findings are as follows. Annually, S1 reduced simulated electricity consumption by 3.27% (1136.42 kWh/year relative to S0), a saving that is modest in absolute terms but operationally meaningful because it requires no envelope retrofit. This benefit was highly seasonal: January, February, March and December accounted for 96.2% of the annual saving, while May to September showed no meaningful reduction, confirming that the strategy is not a year-round substitute for air-conditioning and, because it contributes nothing during peak summer, should not be promoted as a standalone peak-load-reduction measure. The January hourly analysis provided the clearest evidence of when the strategy is useful, showing 425 zero-cooling hours out of 744 (57.1%) and cooling representing only 12.6% of January electricity use against 51.4% for lighting and 36.0% for pumps, indicating that residual winter electricity demand is dominated by non-cooling end uses rather than cooling itself. Thermal-comfort indicators (mean PMV +0.94; only 0.5% of hours within the $\pm$0.5 PMV band) show that these savings are accompanied by a measurable comfort trade-off on the stricter PMV metric, one that this simulation-only study does not fully resolve and that should be re-examined against field-based adaptive-comfort data.

The primary takeaway is that controlled night ventilation in Bahrain is a selective, cooler-season strategy rather than a universal solution: its performance is specific to the single building configuration and orientation modelled here (Section 6), and its household-level economic case under Bahrain's subsidised electricity tariff is modest (Section 5.4).

It should therefore be positioned as a complement to, not a substitute for, envelope and HVAC-efficiency upgrades, which remain the priority for reducing peak summer demand.

These findings carry direct policy and practical implications. For planning and regulation, seasonal, humidity-aware ventilation guidance could be incorporated into building codes, housing manuals and public-awareness programmes, positioned below envelope and HVAC-efficiency requirements rather than in place of them. For design and implementation, the results support operable windows, secure night-opening provisions, and, where justified by future cost-feasibility analysis, simple sensor-based or automated control informed by outdoor temperature, humidity and dew point; because January electricity use was dominated by lighting and pump loads, night ventilation should also be paired with internal-gain reduction measures such as efficient lighting and equipment management.

In conclusion, controlled night ventilation is not a complete solution to Bahrain's residential cooling challenge, but it is a practical, low-cost component of a wider low-energy housing strategy when positioned correctly within the policy mix and its comfort and economic trade-offs are acknowledged rather than understated. By reducing residential cooling electricity without requiring building-fabric retrofit, the strategy supports the United Nations' Sustainable Development Goals, particularly SDG 7 (affordable and clean energy), SDG 11 (sustainable cities and communities) and SDG 13 (climate action), offering a scalable pathway toward more sustainable residential cooling in similar hot–arid Gulf contexts.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The author declares no conflicts of interest.

References

1. International Energy Agency. Buildings. Available online: https://www.iea.org/energy-system/buildings (accessed on 20 May 2026).
2. United Nations Environment Programme; Global Alliance for Buildings and Construction. *Global Status Report for Buildings and Construction 2024/2025: Not Just Another Brick in the Wall*; UNEP: Nairobi, Kenya, 2025.
3. Intergovernmental Panel on Climate Change. *Climate Change 2022: Mitigation of Climate Change*; Cambridge University Press: Cambridge, UK, 2022.
4. Perez-Lombard, L.; Ortiz, J.; Pout, C. A review on buildings energy consumption information. *Energy Build.* **2008**, *40*, 394–398. [CrossRef]
5. Akbari, H.; Morsy, M.G.; Al-Baharna, N.S. *Electricity Savings Potentials in the Residential Sector of Bahrain*; Lawrence Berkeley National Laboratory: Berkeley, CA, USA, 1996.
6. Al-Badi, A.; AlMubarak, I. Growing energy demand in the GCC countries. *Arab J. Basic Appl. Sci.* **2019**, *26*, 488–496. [CrossRef]
7. Dubey, K.; Krarti, M. *An Evaluation of High Energy Performance Residential Buildings in Bahrain*; King Abdullah Petroleum Studies and Research Center: Riyadh, Saudi Arabia, 2017.
8. Krarti, M.; Dubey, K. Benefits of energy efficiency programs for residential buildings in Bahrain. *J. Build. Eng.* **2018**, *18*, 40–50. [CrossRef]
9. Elnabawi, M.H. Evaluating the impact of energy efficiency building codes for residential buildings in the GCC. *Energies* **2021**, *14*, 8088. [CrossRef]
10. Akbari, H. Measured energy savings from the application of reflective roofs in two small non-residential buildings. *Energy* **2003**, *28*, 953–967. [CrossRef]

11. Baniassadi, A.; Sailor, D.J.; Crank, P.J.; Ban-Weiss, G.A. Direct and indirect effects of high-albedo roofs on energy consumption and thermal comfort of residential buildings. *Energy Build.* **2018**, *178*, 71–83. [CrossRef]
12. Dabaieh, M.; Wanas, O.; Hegazy, M.A.; Johansson, E. Reducing cooling demands in a hot dry climate: A simulation study for non-insulated passive cool roof thermal performance in residential buildings. *Energy Build.* **2015**, *89*, 142–152. [CrossRef]
13. Elnabawi, M.H.; Saber, E. Reducing carbon footprint and cooling demand in arid climates using an integrated hybrid ventilation and photovoltaic approach. *Environ. Dev. Sustain.* **2022**, *24*, 3396–3418. [CrossRef]
14. Gagliano, A.; Detommaso, M.; Nocera, F.; Evola, G. A multi-criteria methodology for comparing the energy and environmental behavior of cool, green and traditional roofs. *Build. Environ.* **2015**, *90*, 71–81. [CrossRef]
15. Synnefa, A.; Saliari, M.; Santamouris, M. Experimental and numerical assessment of the impact of increased roof reflectance on a school building in Athens. *Energy Build.* **2012**, *55*, 7–15. [CrossRef]
16. Sedki, A. Sustainable decision-making in urban design: Softscape solutions for mitigating urban heat island effects in hot-arid climates. In *Proceedings of the 2024 International Conference on Decision Aid Sciences and Applications (DASA), Manama, Bahrain, 11–12 December 2024*; IEEE: New York, NY, USA, 2024; pp. 1–5.
17. Sedki, A.; Awawdeh, S.; Elzefzafy, H. Optimizing outdoor thermal comfort with pedestrian-based urban greenery planning: A microclimate simulation study. In *Proceedings of the 2024 International Conference on Decision Aid Sciences and Applications (DASA), Manama, Bahrain, 11–12 December 2024*; IEEE: New York, NY, USA, 2024; pp. 1–6.
18. Haldi, F.; Robinson, D. Interactions with window openings by office occupants. *Build. Environ.* **2009**, *44*, 2378–2395. [CrossRef]
19. Indraganti, M. Adaptive use of natural ventilation for thermal comfort in Indian apartments. *Build. Environ.* **2010**, *45*, 1490–1507. [CrossRef]
20. Rijal, H.B.; Tuohy, P.; Humphreys, M.A.; Nicol, J.F.; Samuel, A.; Clarke, J. Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings. *Energy Build.* **2007**, *39*, 823–836. [CrossRef]
21. Yun, G.Y.; Steemers, K. Time-dependent occupant behaviour models of window control in summer. *Build. Environ.* **2008**, *43*, 1471–1482. [CrossRef]
22. Brager, G.S.; de Dear, R.J. Thermal adaptation in the built environment: A literature review. *Energy Build.* **1998**, *27*, 83–96. [CrossRef]
23. de Dear, R.J.; Brager, G.S. Developing an adaptive model of thermal comfort and preference. *ASHRAE Trans.* **1998**, *104*, 145–167.
24. Humphreys, M.A.; Nicol, J.F. Understanding the adaptive approach to thermal comfort. *ASHRAE Trans.* **1998**, *104*, 991–1004.
25. Nicol, F.; Humphreys, M. Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy Build.* **2002**, *34*, 563–572.
26. Borgeson, S.; Brager, G. Comfort standards and variations in exceedance for mixed-mode buildings. *Build. Res. Inf.* **2011**, *39*, 118–133. [CrossRef]
27. Brager, G.S.; Baker, L. Occupant satisfaction in mixed-mode buildings. *Build. Res. Inf.* **2009**, *37*, 369–380. [CrossRef]
28. Ezzeldin, S.; Rees, S.J. The potential for office buildings with mixed-mode ventilation and low energy cooling systems in arid climates. *Energy Build.* **2013**, *65*, 368–381. [CrossRef]
29. Artmann, N.; Manz, H.; Heiselberg, P. Climatic potential for passive cooling of buildings by night-time ventilation in Europe. *Appl. Energy* **2007**, *84*, 187–201. [CrossRef]
30. Blondeau, P.; Sperandio, M.; Allard, F. Night ventilation for building cooling in summer. *Sol. Energy* **1997**, *61*, 327–335. [CrossRef]
31. Givoni, B. *Climate Considerations in Building and Urban Design*; Wiley: New York, NY, USA, 1998.
32. Shaviv, Y.; Yezioro, A.; Capeluto, I.G. Thermal mass and night ventilation as passive cooling design strategy. *Renew. Energy* **2001**, *24*, 445–452. [CrossRef]
33. Sedki, A.; Hamza, N.; Zaffagnini, T. Effectiveness of occupant behavioral ventilation strategies on indoor thermal comfort in hot arid climate. In *Sustainable Building for a Cleaner Environment*; Sayigh, A., Ed.; Springer: Cham, Switzerland, 2019; pp. 15–24. [CrossRef]
34. Al Niyadi, S.; Elnabawi, M.H. Optimizing hybrid ventilation in arid climates: A systematic review and Dubai case study. *City Environ. Interact.* **2025**, *26*, 100191. [CrossRef]
35. *ASHRAE Guideline 14-2014*; Measurement of Energy, Demand, and Water Savings. ASHRAE: Atlanta, GA, USA, 2014.
36. Fanger, P.O. *Thermal Comfort: Analysis and Applications in Environmental Engineering*; Danish Technical Press: Copenhagen, Denmark, 1970.
37. *ANSI/ASHRAE Standard 55-2023*; Thermal Environmental Conditions for Human Occupancy. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE): Atlanta, GA, USA, 2023.
38. *EN 16798-1*; Energy Performance of Buildings—Ventilation for Buildings—Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings. European Committee for Standardization, CEN: Brussels, Belgium, 2019.

39. *ISO 7730*; Ergonomics of the Thermal Environment—Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria. International Organization for Standardization (ISO): Geneva, Switzerland, 2005.
40. Olesen, B.W.; Parsons, K.C. Introduction to thermal comfort standards and to the proposed new version of EN ISO 7730. *Energy Build.* **2002**, *34*, 537–548. [CrossRef]
41. Elnabawi, M.H.; Tabet Aoul, K.A.; Alhumaidi, A.; Osman, B.; Alshehhi, R.; AlMahri, S. A behavioural analysis of outdoor thermal comfort in a hot, arid climate: A culture and gender equality perspective. *Archit. Sci. Rev.* **2025**, *68*, 41–55. [CrossRef]
42. Humphreys, M.A.; Nicol, J.F.; Roaf, S. *Adaptive Thermal Comfort: Foundations and Analysis*; Routledge: Abingdon, UK, 2016.
43. Nicol, F. Adaptive thermal comfort standards in the hot-humid tropics. *Energy Build.* **2004**, *36*, 628–637. [CrossRef]
44. Sedki, A.; Hamza, N.; Zaffagnini, T. Correlation between retrofitting building envelope and thermal improvement on social housing in hot-arid climate. In *Proceedings of the BSO 2016 Building Simulation and Optimization Conference, Newcastle upon Tyne, UK, 12–14 September 2016*; Newcastle University: Newcastle upon Tyne, UK, 2016; p. 55.
45. Allard, F. (Ed.) *Natural Ventilation in Buildings: A Design Handbook*; James & James: London, UK, 1998.
46. Asimakopoulos, D.; Santamouris, M. *Passive Cooling of Buildings*; James & James: London, UK, 1996.
47. Givoni, B. *Passive and Low Energy Cooling of Buildings*; Wiley: New York, NY, USA, 1994.
48. Santamouris, M. (Ed.) *Advances in Passive Cooling*; Earthscan: London, UK, 2007.
49. Geros, V.; Santamouris, M.; Tsangrassoulis, A.; Guarracino, G. Experimental evaluation of night ventilation phenomena. *Energy Build.* **1999**, *29*, 141–154. [CrossRef]
50. Kolokotroni, M.; Aronis, A. Cooling-energy reduction in air-conditioned offices by using night ventilation. *Appl. Energy* **1999**, *63*, 241–253. [CrossRef]
51. Pfafferott, J.; Herkel, S.; Wambsganss, M. Design, monitoring and evaluation of a low energy office building with passive cooling by night ventilation. *Energy Build.* **2004**, *36*, 455–465. [CrossRef]
52. Oropeza-Perez, I.; Ostergaard, P.A. Energy saving potential of utilizing natural ventilation under warm conditions—A case study of Mexico. *Energy Build.* **2014**, *80*, 520–531. [CrossRef]
53. Chartered Institution of Building Services Engineers. *Natural Ventilation in Non-Domestic Buildings (AM10)*; CIBSE: London, UK, 2005.
54. Gado, T.; Osman, M. Investigating natural ventilation inside walk-up housing blocks in the Egyptian desert climatic design region. *Int. J. Vent.* **2009**, *8*, 145–160. [CrossRef]
55. Chartered Institution of Building Services Engineers. *Environmental Design: CIBSE Guide A*; CIBSE: London, UK, 2006.
56. Daaboul, J.; Ghali, K.; Ghaddar, N. Mixed-mode ventilation and air conditioning as alternative for energy savings: A case study in Beirut current and future climate. *Energy Effic.* **2018**, *11*, 13–30.
57. Annan, G.; Ghaddar, N.; Ghali, K. Natural ventilation in Beirut residential buildings for extended comfort hours. *Int. J. Sustain. Energy* **2014**, *35*, 996–1013. [CrossRef]
58. Crawley, D.B.; Lawrie, L.K.; Winkelmann, F.C.; Buhl, W.F.; Huang, Y.J.; Pedersen, C.O.; Strand, R.K.; Liesen, R.J.; Fisher, D.E.; Witte, M.J.; et al. EnergyPlus: Creating a new-generation building energy simulation program. *Energy Build.* **2001**, *33*, 319–331. [CrossRef]
59. Crawley, D.B.; Hand, J.W.; Kummert, M.; Griffith, B.T. Contrasting the capabilities of building energy performance simulation programs. *Build. Environ.* **2008**, *43*, 661–673. [CrossRef]
60. DesignBuilder Software Ltd. *DesignBuilder Software Documentation*; DesignBuilder Software Ltd.: Stroud, UK, 2024.
61. EnergyPlus. *EnergyPlus Engineering Reference*; U.S. Department of Energy: Washington, DC, USA, 2024.
62. Attia, S.; Hensen, J.L.M.; Beltran, L.; De Herde, A. Selection criteria for building performance simulation tools: Contrasting architects' and engineers' needs. *J. Build. Perform. Simul.* **2012**, *5*, 155–169. [CrossRef]
63. Attia, S.; Hamdy, M.; O'Brien, W.; Carlucci, S. Assessing gaps and needs for integrating building performance optimization tools in net zero energy buildings design. *Energy Build.* **2013**, *60*, 110–124. [CrossRef]
64. Clarke, J.A. *Energy Simulation in Building Design*, 2nd ed.; Butterworth-Heinemann: Oxford, UK, 2001.
65. Elnabawi, M.H.; Hamza, N. Investigating building information model (BIM) to building energy simulation (BES): Interoperability and simulation results. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *397*, 012013. [CrossRef]
66. Hensen, J.L.M.; Lamberts, R. (Eds.) *Building Performance Simulation for Design and Operation*; Spon Press: Abingdon, UK, 2011.
67. Maile, T.; Fischer, M.; Bazjanac, V. *Building Energy Performance Simulation Tools—A Life-Cycle and Interoperable Perspective*; CIFE Working Paper 107; Stanford University: Stanford, CA, USA, 2007.
68. Nie, H.; Sedki, A. BIM building HVAC energy saving technology based on fractional differential equation. *Appl. Math. Nonlinear Sci.* **2022**, *7*, 491–498. [CrossRef]

69. Cipriano, J.; Mor, G.; Chemisana, D.; Perez, D.; Gamboa, G.; Cipriano, X. Evaluation of a multi-stage guided search approach for the calibration of building energy simulation models. *Energy Build.* **2015**, *87*, 370–385. [CrossRef]
70. Maamari, F.; Andersen, M.; de Boer, J.; Carroll, W.L.; Dumortier, D.; Greenup, P. Experimental validation of simulation methods for bi-directional transmission properties at the daylighting performance level. *Energy Build.* **2006**, *38*, 878–889. [CrossRef]
71. Jinhai, Z.; Ye, H.; Shaobin, W.; Sedki, A. Preservation and utilisation of historic buildings in old district of Guangzhou from the perspective of space syntax. *Appl. Math. Nonlinear Sci.* **2022**, *7*, 931–956. [CrossRef]
72. Peel, M.C.; Finlayson, B.L.; McMahon, T.A. Updated world map of the Koppen-Geiger climate classification. *Hydrol. Earth Syst. Sci.* **2007**, *11*, 1633–1644. [CrossRef]
73. de Dear, R.; Akimoto, T.; Arens, E.A.; Brager, G.; Candido, C.; Cheong, K.W.D.; Li, B.; Nishihara, N.; Sekhar, S.C.; Tanabe, S.; et al. Progress in thermal comfort research over the last twenty years. *Indoor Air* **2013**, *23*, 442–461. [CrossRef] [PubMed]
74. Elnabawi, M.H.; Jamei, E. The thermal perception of outdoor urban spaces in a hot arid climate: A structural equation modelling (SEM) approach. *Urban Clim.* **2024**, *55*, 101969. [CrossRef]
75. Oke, T.R. The energetic basis of the urban heat island. *Q. J. R. Meteorol. Soc.* **1982**, *108*, 1–24. [CrossRef]
76. Sedki, A. Evaluating the influence of old and new rental systems on the physical condition of historic mixed-use buildings: A case study of Lebanon. *Front. Built Environ.* **2023**, *9*, 1190374. [CrossRef]
77. Bhatia, A.; Mathur, J.; Garg, V. Calibrated simulation for estimating energy savings by the use of cool roof in five Indian climatic zones. *J. Renew. Sustain. Energy* **2011**, *3*, 023108. [CrossRef]
78. Bruse, M.; Fleer, H. Simulating surface-plant-air interactions inside urban environments with a three dimensional numerical model. *Environ. Model. Softw.* **1998**, *13*, 373–384. [CrossRef]
79. Cao, M.; Rosado, P.; Lin, Z.; Levinson, R.; Millstein, D. Cool roofs in Guangzhou, China: Outdoor air temperature reductions during heat waves and typical summer conditions. *Environ. Sci. Technol.* **2015**, *49*, 14672–14679. [CrossRef] [PubMed]
80. Dominguez-Delgado, A.; Dominguez-Torres, H.; Dominguez-Torres, C.-A. Energy and economic life cycle assessment of cool roofs applied to the refurbishment of social housing in Southern Spain. *Sustainability* **2020**, *12*, 5602. [CrossRef]
81. Elsarrag, E.; Alhorr, Y. Modelling the thermal energy demand of a passive-house in the Gulf region: The impact of thermal insulation. *Int. J. Sustain. Built Environ.* **2012**, *1*, 1–15. [CrossRef]
82. Falasca, S.; Ciancio, V.; Salata, F.; Golasi, I.; Rosso, F.; Curci, G. High albedo materials to counteract heat waves in cities: An assessment of meteorology, buildings energy needs and pedestrian thermal comfort. *Build. Environ.* **2019**, *163*, 106242. [CrossRef]
83. Ferrara, M.; Fabrizio, E.; Virgone, J.; Filippi, M. A simulation-based optimization method for cost-optimal analysis of nearly zero energy buildings. *Energy Build.* **2014**, *84*, 442–457. [CrossRef]
84. Forouzandeh, A. Prediction of surface temperature of building surrounding envelopes using holistic microclimate ENVI-met model. *Sustain. Cities Soc.* **2021**, *70*, 102878. [CrossRef]
85. Frontczak, M.; Wargocki, P. Literature survey on how different factors influence human comfort in indoor environments. *Build. Environ.* **2011**, *46*, 922–937. [CrossRef]
86. Griego, D.; Krarti, M.; Hernandez-Guerrero, A. Optimization of energy efficiency and thermal comfort measures for residential buildings in Salamanca, Mexico. *Energy Build.* **2012**, *54*, 540–549. [CrossRef]
87. Han, T.; Huang, Q.; Zhang, A.; Zhang, Q. Simulation-based decision support tools in the early design stages of a green building—A review. *Sustainability* **2018**, *10*, 3696. [CrossRef]
88. Hernandez-Perez, I. Influence of traditional and solar reflective coatings on the heat transfer of building roofs in Mexico. *Appl. Sci.* **2021**, *11*, 3263. [CrossRef]
89. Hernandez-Perez, I.; Alvarez, G.; Xaman, J.; Zavala-Guillen, I.; Arce, J.; Sima, E. Thermal performance of reflective materials applied to exterior building components. *Energy Build.* **2014**, *80*, 81–105. [CrossRef]
90. Liu, J.; Yao, R.; Wang, J.; Li, B. Occupants' behavioural adaptation in workplaces with non-central heating and cooling systems. *Appl. Therm. Eng.* **2012**, *35*, 40–54. [CrossRef]
91. Nicol, F. An analysis of some observations of thermal comfort in Roorkee, India and Baghdad, Iraq. *Ann. Hum. Biol.* **1974**, *1*, 411–426. [CrossRef] [PubMed]
92. Roaf, S.; Fuentes, M.; Thomas, S. *Ecohouse: A Design Guide*; Architectural Press: Oxford, UK, 2001.
93. Solmaz, A.S. A critical review on building performance simulation tools. *Alam Cipta Int. J. Sustain. Trop. Des. Res. Pract.* **2019**, *12*, 7–21. [CrossRef]
94. Szokolay, S.V. *Introduction to Architectural Science: The Basis of Sustainable Design*, 2nd ed.; Elsevier: Oxford, UK, 2008.
95. Todeschi, V.; Mutani, G.; Baima, L.; Nigra, M.; Robiglio, M. Smart solutions for sustainable cities—The re-coding experience for harnessing the potential of urban rooftops. *Appl. Sci.* **2020**, *10*, 7112. [CrossRef]
96. Tsoka, S.; Tolika, K.; Theodosiou, T.; Tsikaloudaki, K.; Bikas, D. A method to account for the urban microclimate on the creation of typical weather year datasets for building energy simulation, using stochastically generated data. *Energy Build.* **2018**, *165*, 270–283. [CrossRef]

97. Tsoka, S.; Tsikaloudaki, A.; Theodosiou, T. Analyzing the ENVI-met microclimate model's performance and assessing cool materials and urban vegetation applications—A review. *Sustain. Cities Soc.* **2018**, *43*, 55–76. [CrossRef]
98. World Bank. *World Development Indicators 2016*; World Bank: Washington, DC, USA, 2016.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.