

A High-Resolution Data-Driven Approach for Calibration of Cooling Energy Models

Morteza Haddadi¹, Abbas Rajabi-Ghahnavieh^{1*}, Natasa Nord²

¹Department of Energy Engineering, Sharif University of Technology, Azadi Ave., Tehran, Iran

²Department of Energy and Process Technology, Norwegian University of Science and Technology, Trondheim, Norway

*Corresponding author: Email: Rajabi@sharif.edu, Fax: +98-21-66081722, Tel.: +98-21-66166105

Keywords

Building energy calibration
Cooling model
Energy Management
Building operation

Abstract

Building energy simulation is widely employed to support sustainable design, retrofit evaluation, and operational decision-making. However, the reliability of such applications depends critically on accurate model calibration. This study proposes a novel calibration methodology for building cooling load models that leverages high-resolution data to enhance accuracy and robustness. The approach extends the ASHRAE Residential Cooling Load Factor method by introducing the Tuning Night and Day Cycle (TNDC) technique, which differentiates between nighttime and daytime thermal dynamics. Specifically, nighttime cooling loads are exploited to identify infiltration rates, while daytime loads are utilized to estimate the solar heat gain coefficient. An integrated simulation framework was developed using EnergyPlus and the Python-based package OpyPlus to implement the proposed method. The approach was validated through a case study of an office building, demonstrating substantial improvements in calibration accuracy: the normalized mean bias error (NMBE) decreased from 44% to 1%, and the coefficient of variation of the root mean square error (CV(RMSE)) was reduced from 53% to 24%. These results highlight the potential of TNDC as a rigorous and scalable strategy for improving building energy model calibration using high-resolution data.

1. Introduction

Buildings are among the most energy-consuming sectors [1]. One-third of the global carbon emissions are generated from residential, commercial, and institutional buildings [2]. Therefore, improving building energy efficiency is considered an effective strategy for carbon reduction in institutions, cities, and buildings.

Cooling energy use represents a significant share of building energy consumption, particularly in hot climates. In recent years, the energy required for cooling has increased considerably due to rising living standards, widespread accessibility of air conditioning systems, elevated urban temperatures, and global climate change [3]. Energy projections for the coming decades indicate that this increasing trend will become even more critical, especially in emerging and growth-led economies that are expected to experience warmer climates [4]. Since a large portion of building energy use is associated with cooling demand, optimal design and operation of air-conditioning systems can significantly improve overall building energy performance [5]. Building energy models are widely used to evaluate energy performance, retrofit strategies, and operational improvements [6]. These models are also applied in building performance monitoring, where simulated results are compared against measured data to assess system behavior and operational correctness [7]. The precision of a simulation model mainly depends on how well the simulated outputs match the available measured data [8]. The degree of confidence in modeling results therefore strongly depends on the calibration level of the building energy model (BEM). In other words, to make BEM a reliable tool for performance assessment and optimization, improved agreement between simulated energy use and measured data has emerged as an essential requirement [9]. Calibration of building energy simulation models has consequently been the focus of many studies [10–12] and a comprehensive review highlights various methodologies for data collection, modeling, and calibration [13].

In order to quantify the benefits of retrofitting, a stochastic-based approach for calibrating building energy models using monthly energy use has been proposed [14]. A calibration methodology for a university building utilizing a genetic algorithm to optimize a large set of input parameters based on monthly energy data was presented in [15]. Bayesian calibration techniques have been employed to generate probabilistic predictions of building performance while accounting for uncertainties related to retrofit interventions [16]. Another calibration approach links parameter tuning with bias pattern recognition based on monthly utility bills [17]. In addition, inverse modeling approaches validated using hourly energy use data have also been investigated [18]. The impact of energy data resolution on model calibration accuracy and retrofit analysis has been examined in [19]. The results show that models calibrated with monthly energy data can exhibit deviations of up to 38% when applied to hourly energy use calculations [19]. Furthermore, a simplified calibration method based on only two weeks of hourly measured cooling and heating data was developed and successfully implemented for an office building [20]. The calibrated model satisfied standard acceptance criteria when evaluated against monthly energy use [20].

A comprehensive discussion on model calibration challenges and the relative importance of model parameters is provided in [21]. Several studies have identified air infiltration and window properties as among the most influential parameters affecting hourly building energy use [22]. In this study, 44 parameters were screened based on assumed uncertainty ranges, and sensitivity analysis revealed that air infiltration and Solar Heat Gain Coefficient (SHGC) were primarily responsible for hourly variations and daily cooling peaks [22]. A comparison between simulation results and utility bills further demonstrated that accurate estimation of air infiltration improves model accuracy, resulting in a 3–11% reduction in CV(RMSE) and a 2–11% reduction in NMBE [23]. The strong influence of SHGC and infiltration on summer hourly cooling loads has also been extensively investigated [24,25].

Air exchange through infiltration or exfiltration has been shown to significantly affect building energy use [26]. A comprehensive analysis of 225 dwellings in Mediterranean cities and the Canary Islands reported an average air change rate of 8.43 ACH at 50 Pa, corresponding to cooling energy impacts between 0.54 and 3.06 kWh/m²·year [26]. Simulation-based studies further highlight this effect. For a typical office building in Changsha, China, reducing air infiltration rates by 94% decreased cooling energy use from 14.29 to 0.75 kWh/m²·year [27]. These findings emphasize the importance of infiltration control for improving cooling energy efficiency.

The International Green Construction Code (IgCC) [28] specifies a maximum infiltration rate of 2 lit/s/m² at a pressure difference of 75 Pa. ASHRAE 90.1 defines a baseline infiltration rate of 9.14 lit/s/m² at the same pressure difference, which is commonly used as a reference for evaluating building airtightness [29]. In addition, ASHRAE 189.1 provides recommended SHGC ranges between 0.19 and 0.5 based on building location and orientation [30].

Recent studies have advanced building energy model calibration using methods such as machine learning surrogates, Bayesian inference, sensitivity analysis, and high-resolution monitoring data [31–39]. Surrogate-based approaches mainly focus on reducing computational time, but often provide limited physical interpretation of calibrated parameters [31]. Bayesian frameworks offer strong uncertainty quantification, yet generally assume that influential parameters remain constant over time [32,33]. Studies using hourly data improve model accuracy, but typically adjust several parameters at once without clearly identifying their dominant temporal effects [34,35]. Simplified and automated calibration approaches improve scalability, but are usually evaluated at aggregated time scales, which limits their ability to capture diurnal cooling behavior [36,37]. Although sensitivity-based studies identify infiltration and SHGC as key cooling-related parameters, temporal variations in their influence are rarely used in the calibration process [38,39]. Overall, existing calibration frameworks do not clearly distinguish between daytime solar-driven cooling loads and nighttime temperature-driven envelope losses. This limitation reduces the identifiability and physical interpretability of cooling-related envelope parameters and highlights the need for calibration approaches that explicitly account for diurnal thermal regimes.

Table 1 summarizes representative building energy model calibration studies and highlights the research gap addressed in this work.

- Calibration data resolution: monthly, daily, hourly
- Calibration method: stochastic, GA, Bayesian, inverse modeling
- Calibrated parameters: multiple parameters, HVAC efficiency, envelope properties
- Explicit separation of daytime/nighttime effects: mostly not addressed
- Data requirements: utility bills, sub-metering, sensors
- **Research gap:** lack of a physically interpretable, hourly calibration method that explicitly separates daytime solar-driven effects and nighttime infiltration-driven effects using high-resolution data
- **This study:** proposes TNDC to address this gap

The objective of this study is to propose an hourly calibration approach for building cooling energy models using high-resolution data. The proposed approach determines SHGC and air exchange, broadly referred to as infiltration, through mathematical formulations describing their relationship with cooling energy use. A novel Tuning Night and Day Cycle (TNDC) technique is introduced, which separates daytime and nighttime energy use to improve parameter identifiability. Using this separation, SHGC is primarily calibrated from daytime energy use, while infiltration is calibrated from nighttime energy use. The resulting calibrated model satisfies standard acceptance criteria based on NMBE and CV(RMSE). To implement the proposed approach, an integrated simulation-based workflow was developed using Energy Plus and the Python-based package OpyPlus. The methodology is applied to a real case study building to evaluate the effectiveness of the proposed calibration approach.

The main contributions of this paper are as follows:

- Development of a novel hourly BEM calibration approach using high-resolution energy data;
- Determination of SHGC and infiltration parameters by explicitly segregating daytime and nighttime energy use;
- Provision of a semi-automatic calibration framework integrating Energy Plus and OpyPlus.

The rest of the paper is organized as follows. Section 2 describes the methodology. Section 3 presents the case study. Section 4 discusses the building energy model and calibration results, and concluding remarks are provided in Section 5.

2. Methodology

Mathematical formulations to describe a novel technique, revealing a crucial relationship between energy use and building parameters, SHGC and infiltration, are introduced and described in this section. Building upon this evidence, the TNDC technique is introduced in this section afterward.

2.1 Background of Proposed Approach

Firstly, to emphasize the critical role of two parameters, SHGC and infiltration on building cooling load, theoretical foundation using the ASHRAE Residential Cooling Load Factor (RLF) method is presented [40]. Subsequently, this will enable us to delve into the details of the TNDC algorithm, which facilitates the precise calculation of SHGC and infiltration. Despite its practicality, the RLF method has limitations, as outlined in the ASHRAE Handbook. Expert knowledge is essential for correct application, as improper use may lead to oversizing or under sizing of HVAC systems. Additionally, the RLF method is most suitable for specific climatic conditions and latitudes. Nevertheless, due to its widespread adoption and adaptability, it serves as a foundational method for load calculations. In our approach, RLF was selected as the basic method for theoretical discussion because evaluating and comparing cooling load during the day and night was essential for our analysis. Based on RLF, building cooling load was obtained as the sum of the following: q_{opc} that represents the cooling load from opaque surfaces (walls, floors, ceilings, and doors), q_{fens} corresponds to the cooling load from fenestration surfaces (windows, skylights, and glazed doors), q_{inf} that is infiltration cooling load, and q_{int} accounts for the internal load (lights, people, appliances, and equipment). The total fenestration cooling load, q_{fens} can be calculated as:

$$q_{fens} = A_f \times CF_{fen} \quad (1)$$

$$CF_{fen} = U_f (\Delta t - 0.46DR) + PXI \times SHGC \times IAC \times FF_s \quad (2)$$

where A_f (m^2) is fenestration area (including frame), CF_{fens} (W/m^2) is surface cooling factor, U_f ($W/m^2 \cdot K$) fenestration U-factor, Δt (K) is the cooling temperature difference, PXI (W/m^2) is the peak exterior irradiance, $SHGC$ is the solar heat gain coefficient, IAC is the interior shading attenuation coefficient, FF_s is the fenestration solar load factor, DR (K) is the cooling daily range. PXI is related to E_t, E_d, E_D (W/m^2) the peak total, diffuse, and direct irradiance respectively. The E_t, E_d, E_D values are too much higher during the daytime than at nighttime, because there is no irradiance during the night. Eq. 2 may be rewritten as Eq.3 and Eq.4, where q_{fens_day} is the fenestration cooling load during the day and the q_{fens_night} is the fenestration cooling load during the night; therefore,

$$q_{fens_day} = A_f U_f (\Delta t - 0.46DR) + A_f \times PXI \times SHGC \times IAC \times FF_s \quad (3)$$

$$q_{fens_night} = A_f U_f (\Delta t - 0.46DR) \quad (4)$$

From Eq.4, it is clear that the cooling load during the night does not depend on SHGC. The infiltration cooling load (q_{inf}) is calculated as:

$$q_{int} = q_s + q_l \quad (5)$$

Infiltration sensible (q_s) load can also be expressed as:

$$q_s = C_s Q_s \Delta t \quad (6)$$

where $C_s = 1.23$ is the air sensible heat factor in $W/(m^3 \cdot s \cdot K)$, Q_s is the air volumetric flow rate in m^3/s and Δt is the air temperature difference across processes in K. Latent infiltration load (q_l) is expressed as:

$$C_{Fopq} = U_{opq} (OF_t \times \Delta t + OF_b + OF_r \times DR) \quad (7)$$

where $C_l = 3010$ is the air latent heat factor in $W/(m^3 \cdot s)$ and Δw is the difference in air humidity ratio between outdoor and indoor air associated with the infiltration process, expressed in kg_w/kg_{da} .

Based on the Sherman and Grimsrud model [41], the infiltration rate can be calculated as:

$$Q_s = \frac{A_l}{1000} \sqrt{C_{ss} |\Delta t| + C_w V_w^2} \quad (8)$$

where Q_s (m^3/s) is the air volumetric flow rate, A_l (cm^2) is building effective air leakage area, C_{ss} is stack coefficient in $(L/S)^2/(cm^4 \cdot K)$, C_w is wind coefficient in $(L/S)^2/(cm^4 \cdot (m/S)^2)$, V_w (m/s) is the average wind speed measured at the local weather station for time interval of calculation. The value of C_{ss} depends on building height and C_w depends on both the shelter class and the height of the building. Based on [40], effective air leakage area can be considered proportional to the building's exposed wall area A_{es} ($A_l \propto A_{es}$).

Based on [42] the ratio of the building exposed wall area to the building floor area is defined as Geometric Efficiency (GE) as:

$$GE = \frac{A_{es}}{A} \quad (9)$$

where A (m^2) is the total building floor area. According to Eq.8 and Eq.9, the airflow rate can be written as:

$$Q_s \propto GE \times A \Delta t^{\frac{1}{2}} \quad (10)$$

The volume of the building depends on floor height, H , and floor area, A , ($V = H \cdot A$). Finally, according to Eq.6, Eq.10 can be rewritten as:

$$q_s \propto GE \times A \Delta t^{\frac{3}{2}} \quad (11)$$

Considering the building's indoor temperature as constant, the sensitivity of the sensible infiltration cooling load (q_s) to the variation in the outdoor temperature (variation in Δt) can be calculated by taking derivation of Eq.11 as:

$$\frac{\partial q_s}{\partial \Delta t} \propto \frac{3}{2} GE \times A \Delta t^{\frac{1}{2}} \quad (12)$$

Dividing both sides of Eq.12 by q_s , and by rearranging, the following will be obtained:

$$\frac{\partial q_s}{q_s} \propto \frac{3}{2} \frac{\partial \Delta t}{\Delta t} \quad (13)$$

Eq. 13 shows that the variation in the sensible infiltration cooling load is highly dependent on the variation in outdoor temperature. For example, if the indoor temperature is fixed at 20°C and the outdoor temperature changes from 30°C to 35°C, 50% change happens in Δt as Δt increases from 10 to 15. In this case, according to Eq.13, the sensible infiltration cooling load increases by 75%.

To recall Eq.5, the infiltration cooling load is composed of the sensible and latent loads. In Eqs. 6-13, it is shown that sensible cooling load highly depends on variation in the outdoor temperature. Based on Eq.7 and in a similar manner, it can be shown that the latent infiltration cooling load (q_l) highly depends on the variation in the outdoor temperature. In general, it can be concluded that the infiltration cooling load depends on the outdoor temperature as shown in Eq.14 in which C_{inf} is always higher than 1.5:

$$\frac{\partial q_{inf}}{q_{inf}} = \frac{C_{inf}}{\Delta t} \frac{\partial \Delta t}{\Delta t} \quad (14)$$

Regarding opaque surface cooling load (q_{opq}), Eqs. 15 and 16 were obtained based on the RLF method as:

$$q_{opq} = A_{opq} \times CF_{opq} \quad (15)$$

$$C_{Fopq} = U_{opq} (OF_t \times \Delta t + OF_b + OF_r \times DR) \quad (16)$$

where A_{opq} (m^2) is the net surface area, CF_{opq} (W/m^2) is surface cooling factor, U ($W/m^2.K$) is the construction U-factor, Δt (K) is the cooling temperature difference, OF_t, OF_b, OF_r are opaque-surface cooling factors, and DR (K) is cooling daily range.

The sensitivity of q_{opq} to the variation in the outdoor temperature as Opaque Load Sensitive Factor (C_{opq}) can be calculated as in Eqs.17 to Eq.20.

$$\frac{\delta q_{opq}}{\delta \Delta t} = U_{opq} A_{opq} OF_t \quad (17)$$

$$\frac{\partial q_{opq}}{q_{opq}} = \frac{U_{opq} A_{opq} OF_t}{U_{opq} A_{opq} (OF_t + \frac{OF_b}{\Delta t} + \frac{OF_r DR}{\Delta t})} \frac{\partial \Delta t}{\Delta t} \quad (18)$$

$$\frac{\partial q_{opq}}{q_{opq}} = C_{opq} \frac{\partial \Delta t}{\Delta t} \quad (19)$$

$$C_{opq} = \frac{OF_t}{OF_t + \frac{OF_b}{\Delta t} + \frac{OF_r DR}{\Delta t}} \quad (20)$$

As OF_t, OF_b, OF_r for the opaque surface is obtained from Table 2.

It can be observed in Eq.20 that the sensitivity of the opaque surface cooling load to the variation in the outdoor temperature depends on Δt . In particular, the smaller values for Δt result in lower values for C_{opq} . Finally, C_{opq} is shown for daily outdoor temperatures in (cooling design day) Fig. 1 was made based on Eq.20 in which OF_t, OF_b, OF_r were set to 1, 8.2, and -0.36, respectively.

Fig. 1, it can be observed that C_{opq} had higher values during the daytime than during the nighttime. The maximum value obtained for C_{opq} was much lower than the minimum value for C_{inf} that was 1.5 as shown in Eqs. 13-14. In particular, the C_{opq} during the nighttime was much smaller than 1.5. Therefore, it can be concluded that the opaque surface cooling load during the nighttime is much less sensible to the variation in the outdoor temperature than the infiltration cooling load. For a regular building that is not fully air-tightened, the magnitude of the infiltration cooling load is much larger than the opaque surface cooling load. Consequently, it can be concluded that the hourly variation in the total building cooling load during the night is mainly attributed

to the infiltration cooling load. In other words, the hourly variation in the total building cooling load during the night can be used to find an accurate infiltration rate for the building.

The transparent fenestration area accounts for at least 30% of the building façade area. At least half of the building's external area is dedicated to the building façade in cases such as building blocks. Therefore at least 15% of the building's external area is dedicated to fenestration. Solar irradiance during summer days can reach 700 W/m² in the hot climates. Solar heat gain is a dominant contributor to the cooling load during the days in the summer days. It can be shown that the hourly variation in solar irradiance has a stronger effect on hourly cooling load than the outside temperature. Thus, the SHGC associated with fenestration can be determined based on hourly variation in the cooling load during the days.

2.2 Proposed TNDC Technique

Fig. 2 presents the proposed TNDC calibration technique. This technique starts from the preparation stage consisting of gathering building properties, weather data, and measured data. Next, daytime and nighttime hours are defined. All nighttime data of the calibration periods were defined as night cooling, and all daytime data of the calibration period were defined as day cooling. Next, TNDC uses the night cooling load to calibrate the infiltration and then uses the day cooling load to calibrate the SHGC associated with the fenestration. It should be remembered that the term “infiltration” in the proposed approach and TNDC represents any building air exchange, whether infiltration or exfiltration.

Initially, the building model was developed and the parameters were set related to the envelope and cooling based on available data or ASHRAE 90.1. Fig. 2 illustrates the two key multipliers in the proposed technique: the Infiltration Rate Multiplier (IRM) and the Solar Gain Multiplier (SGM). These multipliers fine-tuned the infiltration and SHGC, respectively. Both multipliers are set to unity at the start. In Stage 1, the total building energy use was calculated during the night using simulated energy ($P_{n,m}$) and actual energy use ($P_{n,a}$) as follows:

$$CV(RMSE) = \frac{\sqrt{\left(\frac{\sum_{i=1}^{N_p} (m_i - s_i)^2}{N_p} \right)}}{\bar{m}} \times 100 \quad (21)$$

$$P_{n,a} = \sum_{night} Q_{t,m}(h) \quad (22)$$

where at hour h , $Q_{t,a}(h)$ is the actual cooling load and $Q_{t,m}(h)$ is the simulated cooling load.

Two commonly used indices, the NMBE and CV(RMSE), were employed to evaluate the performance of the calibrated building energy model [43–48]. NMBE serves as a non-dimensional bias measure, capturing the mean difference between measured and simulated data as:

$$NMBE = \frac{\sum_{i=1}^{N_p} (m_i - s_i)}{\sum_{i=1}^{N_p} m_i} \times 100 \quad (23)$$

where m_i and s_i are the measured and simulated data points, respectively. N_p - is the number of data points at interval ‘p’. CV (RMSE), determining how well a model fits the data and it is calculated as:

$$CV(RMSE) = \frac{\sqrt{\frac{\sum_{i=1}^{N_p} (m_i - s_i)^2}{N_p}}}{\bar{m}} \times 100 \quad (24)$$

ASHRAE Guideline 14 outlines specific criteria to assess the accuracy of the building energy model performance [43]. For monthly predictions, the NMBE should not exceed 5%, while the CV(RMSE) should remain below 15%. In the case of hourly predictions, the NMBE limit is 10%, and the CV(RMSE) should not exceed 30%. If the NMBE and CV(RMSE) fail to satisfy the hourly criteria, or if the CV(RSME) continues to decrease, the simulated energy ($P_{n,m}$) and actual energy use ($P_{n,a}$) were employed to update the IRM as follows:

$$IRM_{updated} = IRM \frac{P_{n,a}}{P_{n,m}} \quad (25)$$

According to Eq. 25, if $P_{n,a}$ exceeds $P_{n,m}$, the IRM is adjusted upwards to a new value, denoted as $IRM_{updated}$. Subsequently, the building energy model underwent another simulation. If the calibration criteria were met and CV (RSME) began to increase, the IRM tuning process was terminated.

In the next stage (Stage 2), after calibrating the cooling load for the nighttime, the total building energy use during the days ($P_{d,m}$) was estimated alongside the actual measured energy use ($P_{d,a}$). Based on the NMBE and CV(RMSE) criteria, the achieved model accuracy was estimated. If the criteria were not met or CV (RSME) continued to decrease, the SGM was updated accordingly:

$$SGM_{updated} = SGM \frac{P_{d,a}}{P_{d,m}} \quad (26)$$

$$P_{d,a} = \sum_{day} Q_{t,a}(h) \quad (27)$$

$$P_{d,m} = \sum_{day} Q_{t,m}(h) \quad (28)$$

Eq. 26 implies that when $P_{d,a}$ exceeded $P_{d,m}$, the SGM was adjusted upward. By setting SGM equal to the updated value $SGM_{updated}$, the model underwent an update. This process was iterated until both the NMBE and CV (RMSE) achieved for the day cooling load or CV (RSME) started increasing from the last iteration. Moving to Stage 3, the updated energy model to calculate the building's 24-hour energy use for the entire tuning period was utilized. If the calibration criteria were met, the tuning algorithm terminated. Otherwise, it returned to Stage 1 to re-update IRM and SGM.

2.3 TNDC Implementation

In the proposed TNDC approach, daytime and nighttime periods are defined based on solar radiation data. Nighttime hours are defined as periods when the global horizontal irradiance (GHI) is equal to zero, while daytime hours correspond to periods with non-zero GHI values. The GHI data are obtained from the weather file used in the simulation, ensuring a consistent and reproducible separation of daytime and nighttime conditions. In the implementation of the TNDC technique, a Python-based script integration with the Energy Plus simulation program was utilized. Specifically, the Python package called Opyplus was leveraged for the BEM calibration [49]. Opyplus facilitates the integration of external Python scripts into the simulation workflow, offering robust features and capabilities for building energy analysis [50]. The script is available on GitHub [51]. Nighttime hours are defined as periods with $GHI \leq 10 \text{ W/m}^2$, while daytime hours correspond to periods with $GHI > 10 \text{ W/m}^2$.

Fig. 3 illustrates the coupling of the Energy Plus model with the Python scripts. This integration is essential for configuring the environmental inputs and criteria metrics toward research objectives that establish a Cooling Energy Model Calibration.

In this study, the RLF formulation is adopted as a theoretical basis to support the physical interpretation of the proposed TNDC approach. The RLF framework explicitly distinguishes between solar-driven heat gains during daytime and temperature-driven loads during nighttime, which provides a clear rationale for separating the calibration process into day and night cycles. It should be noted that RLF is not used here as a detailed cooling load calculation method, but rather as a conceptual framework to explain parameter sensitivity and identifiability. Alternative theoretical bases could also be employed to support the TNDC concept, including heat-balance methods, energy-balance formulations, or sensitivity-based approaches derived from first-principles building physics. Therefore, the proposed TNDC methodology is not limited to the RLF formulation and can be generalized to other physically consistent modeling frameworks.

In the TNDC methodology, two separate objective functions are defined for nighttime and daytime periods. The nighttime objective function quantifies the discrepancy between measured and simulated cooling energy use during nighttime hours, when solar gains are negligible. This objective function is primarily used to tune the infiltration-related parameters. Similarly, the daytime objective function evaluates the discrepancy between measured and simulated cooling energy use during daytime hours, when solar radiation is present, and is used to tune the SHGC. By separating the objective functions in this manner, the identifiability of key parameters is improved.

2.3.1. Parameter credibility and validation strategy

The credibility of the calibrated parameters is ensured through a combination of statistical validation, physical plausibility checks, and independent evidence. From a statistical perspective, the calibrated model satisfies standard acceptance criteria for hourly calibration based on NMBE and CV(RMSE). From a physical standpoint, the calibrated infiltration parameter falls within reasonable ranges when converted to standard infiltration indicators, and the calibrated SHGC is interpreted as an effective value reflecting combined solar-related effects rather than a nominal glazing property. Finally, the consistency of the calibrated parameters with building standards and observed retrofit measures provides additional confidence in the reliability of the proposed approach.

2.3.2. Theoretical and practical limitations of the TNDC method

The proposed TNDC calibration method has several theoretical and practical limitations that should be considered when interpreting the results. From a theoretical perspective, the method relies on the separation of daytime and nighttime energy use to improve parameter identifiability. However, certain model parameters, such as infiltration, SHGC, internal gains, and HVAC operational characteristics, may still exhibit coupling effects that cannot be fully eliminated. In addition, the approach assumes negligible solar gains during nighttime hours, which may introduce minor uncertainties under specific conditions. Moreover, the current implementation focuses on calibrating two key parameters, namely infiltration and SHGC, while other parameters are assumed to remain constant.

From a practical standpoint, the TNDC method requires high-resolution energy use data to enable reliable separation of daytime and nighttime periods. Buildings with only monthly or low-resolution energy data may not be suitable for direct application of the method. Furthermore, significant operational changes, manual interventions, or non-standard control strategies during the calibration period may affect the robustness of the calibrated parameters. Finally, the effectiveness of the day-night separation may be reduced in buildings with limited window areas or highly variable shading conditions.

3. Case Study

3.1 Main Attributes

In implementation of the proposed approach, an educational building was selected as the case study. This section provides a detailed description of the building's main attributes. The chosen building, shown in Fig. 4, is situated near the campus of Sharif University of Technology in Tehran, Iran. It consists of symmetrical Northern and Southern blocks interconnected by corridors.

As shown in Fig. 4, the case study comprises 14 HVAC zones in five stories, including a basement, ground floor, and three upper floors. Adjacent to the Western side of the building, an amphitheater and a library contribute to a total conditioned space area of 4,775 m². Notably, substantial portions of the Southern and Eastern façades feature window coverage. Additionally, the roof incorporates a skylight spanning of 44.8 m².

Table 3 shows the properties of the case building envelope. According to the properties in the last column of Table 3, 35 % of the case building envelope is covered with fenestration. The building relies on natural gas for both cooling and heating. Specifically, the annual gas use intensity is 40.5 Nm³/m²yr or 405 kWh/m²yr. The case building used over 169,000 Nm³ of natural gas in 2014. However, this energy intensity significantly deviates from the prescribed energy standard intensity for educational buildings outlined in the Iranian standard Building [52].

3.2 Basic Parameters of Case Study Building

The detailed energy audit was first accomplished, and the information associated with the HVAC system and envelope of the case study was identified. Energy Plus software has been used to develop the building energy model in which HVAC zones have been included. Table 4 and 5 show the composition of the external walls, roof, and glazing, from which the initial estimate based on ASHRAE 189.1 for SHGC were obtained [30].

The two-week study period coincided with the educational summer vacation. This fact provided reliable information related to internal loads including occupant presence and the setpoint for the indoor temperature. The setpoints were set as the following, for weekdays 24°C and weekends 27°C. In the summer, the internal load in the building consists of lighting at 3 W/m² and plug loads at 3 W/m². Additionally, there were nine occupants present.

The data associated with the HVAC zones and HVAC system were utilized to develop a comprehensive HVAC model for the case study in Energy Plus encompassing all HVAC zones, as shown in Fig. 5.

To supply cooling demand, a powerful HVAC system was deployed in the case study building. The HVAC system uses a combination of air handling units (AHU) and fan coil (FC) units. Natural-gas direct-fired absorption chiller is used for providing cooling. Table 6 presents the main characteristics of the case study HVAC components. The case study comprises 14 HVAC zones for which the basic information and the associated HVAC components are presented in Table 7.

Commonly references and standards specify air leakage rate of building envelope acceptance criteria in terms of lit/s/m², typically at a pressure difference of 75 or 50 Pa. To apply this criterion within the EnergyPlus software, which models building performance under normal conditions, it is necessary to use adjusted values corresponding to the building's normal pressure conditions. The ASHRAE Standard 90.1 provides equations and conditions for applying criteria based on building specifications [53].

According to ASHRAE Standard 90.1, the baseline air infiltration rate of the building envelope is set to 1.8 cfm/sf or 9.14 lit/s/m² at 75 Pa over pressure difference between indoor and outdoor for all the HVAC zones [54]. Considering the envelope specifications of the case study and at a reference wind speed of 4.47 m/s, the baseline for infiltration under the normal pressure is 1.2 lit/s/m² or 1.4 ACH which was used as the initial point in our model [54].

3.3 Building Data Gathering

As natural gas constitutes the primary energy source for the HVAC system in the case study building, see Fig. 5, hourly gas use was required to be collected to provide data for $P_{d,a}$ and $P_{n,a}$ as the main input for the model calibration. The gas meter of the building is a conventional volumetric gas meter without a data logger. As all historical data has been generated by the meter, there is no possibility of changing the meter with a smart one. Another solution was to add a smart meter in series with the actual meter, but that entailed a specific requirement that was not met. To cope with this challenge, a system called Smart Reading System (SRS) was installed in front of the numerator of the gas meter. Using image processing techniques, the digits of the numerator were read and recorded once each hour. The digits were then used to calculate the hourly gas use. The SRS was

installed at the case building on June 10th, 2015. The measurement period of the two weeks from July 27th to August 6th has been chosen as the calibration period for tuning the cooling model.

To evaluate the performance of the calibrated model, two specific days, July 21st (a working day) and July 24th (a weekend day), were selected, because both fell outside the calibration period. Additionally, for monthly validation, the case building gas use data from June to September were analyzed. The simulation results were then compared with the 5-year average monthly usage during the same months.

4. Results on Building Model Calibration

This section outlines the methodology employed to calibrate the cooling energy model for the case educational building. Initially, the baseline parameters were used to develop BEM. Subsequently, the performance of the uncalibrated BEM was evaluated. To achieve calibration, the optimization parameters based on two weeks of hourly data were extracted. Finally, the calibrated model using data from days beyond the calibration period was validated.

4.1 Pre-Calibration Result

Following the development of the initial EnergyPlus model based on a detailed audit, the initial simulation using weather data specific to Tehran city was conducted. The ambient temperature for Tehran was obtained from [55]. As mentioned in Section 3, the pre-calibration infiltration rate was equivalent to 1.2 lit/s/m² at normal pressure and SHGC was 0.2. Therefore, the simulated pre-calibrated model assumes the baseline standard for infiltration and SHGC. The results for the pre-calibrated model along with the measured cooling gas use are presented in Fig. 6.

The results show that the values obtained from the pre-calibrated modeling have a significant difference from the actual values. The parameters CV(RMSE) and NMBE are 53% and 44%, respectively, and they have a significant and meaningful difference from the acceptance criteria. These results indicated that the BEM needed to be deeply calibrated.

4.2 TNDC Application Results

The TNDC technique was deployed to calibrate the model as explained in Sections 2.2 and 2.3. Initially, the calibration of hourly gas usage for 14 nights, associated with the calibration period, was accomplished and the initial corrected value for Infiltration was obtained. To find the minimum night CV(RSME), the infiltration rate was increased from 1.2 to 4.0 lit/s/m² (1.4 to 4.6 ACH) based on SGM = 1 (SHGC = 0.2). The results on variations in CV(RSME) for the night hourly gas use versus the air infiltration rate are shown in Fig. 7. As can be noted in Fig. 7, the CV(RSME) value got lower as the air infiltration rate increased but started again to increase after a certain value of the air infiltration rate.

Investigating the results in Fig. 7, a significant reduction in the night CV(RSME) was observed when the infiltration rate increased from 1.2 to 2.8 lit/s/m² (3.2 ACH), corresponding to IRM = 2.3. Specifically, the night CV(RSME) decreased from 51 to 13%, which is lower than the ASHRAE Guideline 14 requirement of 30% for the hourly BEM [43]. Consequently, the corrected value for IRM was set at 2.3 that fitted to the minimum value of CV(RSME) that equal to 2.8 lit/s/m² or air change per hour 3.2 (ACH). The duration curves for the calibrated and measured night gas use for the night period are shown in Fig. 8. The values for the calibrated BEM are corresponding to IRM of 2.3 and SGM of 1.

For the results in Fig. 8, NMBE and CV(RSME) associated with the night gas duration curve were 6% and 13% respectively, both in the acceptable range based on the ASHRAE Guideline 14 requirement of 30% for the hourly BEM. Keeping IRM at 2.3, the tuning for hourly gas use during 14 days was done to find the corrected SGM. SHGC was increased from 0.2 to 0.9, and similar to Fig. 7, variation in CV (RSME) for the days was analyzed. The minimum CV (RSME) was obtained for SHGC = 0.6 corresponding to SGM = 3, this shows that daytime energy use is directly influenced by the SHGC. The duration curves for the calibrated and measured gas use for the daytime are given in Fig. 9.

Finally, the corrected values for IRM and SGM were set to 2.3 and 3, respectively. The BEM was re-evaluated for the entire 24-hour day of the 2-week calibration period. At this stage, the corrected IRM was again calculated as 2.3, and the optimum

IRM was set to 2.3. Regarding SGM, as shown in Fig. 10, the optimal value was set to 4 (SHGC = 0.8). Based on IRM = 2.3 (infiltration = 2.8 lit/s/m²) and SGM = 4, the 24-hour gas use duration curve was obtained as shown in Fig. 11.

The simulated and measured hourly gas use are given in Fig. 12 for the two-week calibration period for which NMBE and CV (RSME) both have met the calibration criteria based on the ASHRAE Guideline 14 requirement of 30% for the hourly BEM [43].

For the simulated gas use, four instances of significant deviations were identified and labeled as cases a, b, c, and d in Fig. 12. In cases a and b, the unexpected chiller shutdown led to a reduction in the gas use on the shutdown day, followed by an increase on the subsequent day. In the cases c and d, unauthorized adjustments to the chiller set point by the operational staff were promptly detected and rectified.

A comparison of the heat gain from windows, opaque surfaces, and the air infiltration on a typical day on July 23rd was performed for the calibrated model and obtained calibrated parameters such as SHGC, infiltration, and opaque surface heat gain. The comparison results are shown in Fig. 13, it can be noted that the amount of heat gains from the infiltration at night was higher than that of the windows. During the day, the heat gain from the windows was higher than the opaque surface. Therefore, the general conclusion made in Section 2 confirms focusing on the air infiltration during the nighttime and using the solar heat gain for the daytime is a proper way for calibration.

According to Table 8, the SHGC requirement based on the ASHRAE 189.1 standard is between 0.19 and 0.5. However, in our model, it was 0.8, which means the windows used do not meet green standards, potentially leading to increased energy usage. Additionally, according to the ASHRAE 90.1, the baseline for the air infiltration rate is 9.14 lit/s/m² at 75 Pa or 1.2 lit/s/m² (1.4 ACH) at normal pressure, while after the calibration of our model, it was obtained as 2.8 lit/s/m² (3.2 ACH) at normal pressure, or 21.3 lit/s/m² at 75 Pa based on [53].

4.3 Validation of the Calibrated Model

To test the calibrated model, two days i.e., July 21st (working day) and 24th (weekend day) were chosen outside the calibration period. The calibration model was done, according to the results Fig. 14.

According to Fig. 14, it can be realized that the simulated gas use was in good accordance with the actual gas use. The difference between the simulated and the actual gas issue was evaluated by NMBE < 10% and CV(RSME) < 30%, which was treated as acceptable according to [43].

Finally, monthly verification was performed for the calibrated model. Based on the historical data for the cooling seasons in Tehran [56], the results of the case building gas use from June to September are presented in Fig. 15. The simulation results were compared with the 5-year average of the monthly use for the same months.

Based on Fig. 15, it can be pointed out that the results obtained by the calibrated energy model were in good accordance with the actual results. NMBE was 3.8% and CV(RSME) was 6%, which ensures the accuracy of the calibrated model. The results presented in Fig. 14 and Fig. 15 show that the energy model was well verified.

4.4 Practical Implementation

The calibrated model revealed significant air leakage, a value that deviated significantly from our expectations and the accepted standards. Based on the data presented in Chapter Ventilation and infiltration ASHRAE fundamental [40], it is evident that only a small number of buildings exhibit an infiltration air change rate exceeding 3 ACH at normal pressure. This discrepancy raised suspicions and prompted a thorough architectural investigation of the building. Before attributing the discrepancy to a model error, we meticulously examined the building's architectural integrity. A detailed inspection focused on the building envelope, revealing major air pathways from the false ceiling to the exterior along the Northern and Southern facades. Fig. 16 illustrates some of these airways within the concealed space of the false ceiling, extending to the well-lit exterior.

The false ceiling was originally intended to remain isolated from the conditioned space, as there was no expectation that any leakage from the false ceiling to the exterior would directly affect the conditioned area. Consequently, it was recommended to address the air pathways connecting the false ceiling and the air conditioning zone. A thorough inspection of the building revealed additional airways between the false ceiling and the conditioned space, as depicted in Fig. 17a. Undoubtedly, this was identified as an architectural flaw that could alter the building's performance conditions, resulting in an infiltration air change rate exceeding 3 ACH at normal pressure. To mitigate air leakage within the building, civil works were implemented during August in August 2015 to effectively isolate the false ceiling space from the conditioned area, as illustrated in Fig. 17b.

The retrofit measures were implemented for the case study building; however, high-resolution post-retrofit cooling energy data were not available within the timeframe of this study to reapply the TNDC method. As a result, a post-retrofit recalibration was not conducted. Nevertheless, applying the proposed TNDC approach after retrofit implementation represents a valuable direction for future work, as it would enable direct quantification of parameter changes, particularly infiltration-related improvements, and provide additional validation of the method's robustness.

5. Conclusions

In this study, the approach for calibrating building cooling load models was proposed aiming to improve the accuracy of the calibrated model. Our proposed technique, called TNDC leverages high-resolution data. The proposed approach focuses on two key parameters: SHGC and Infiltration. During the daytime, SHGC significantly impacts the cooling loads, therefore, adjustments were made based on the observed cooling load data. For the nighttime cooling loads, the air infiltration plays an important role, and the suggested approach tunes the air infiltration rate using the night cooling load data. The combination of these adjustments led to a more accurate BEM. The approach was applied to a building over two consecutive weeks. Hourly data were collected and the pre-calibrated model served as a baseline. The approach successfully reduced the NMBE and CV(RMSE) for the hourly BEM from 44% and 53% (pre-calibrated) to 1% and 24%, respectively, which is in accordance with the ASHRAE Guideline 14 calibration requirements.

The results showed that the TNDC technique operated effectively with short-term, high-resolution data. Its straightforward algorithm made it suitable for scripts and automation, and it can be seamlessly integrated into building management systems.

Further evaluation of the TNDC effectiveness for other building types would be beneficial. Additionally, assessing its applicability to calibrating heating energy models remains unexplored, despite the negligible heating energy use in the case study building.

In summary, the TNDC technique offers a promising solution for improving cooling load models, enhancing building performance, and advancing energy-efficient designs. Further research and validation will strengthen its applicability across diverse building types.

Acknowledgments

This publication has been jointly written within the cooperative project "Key technologies and demonstration of combined cooling, heating, and power generation for low-carbon neighborhoods/buildings with clean energy – ChiNoZEN". The authors gratefully acknowledge the funding support from the Research Council of Norway (NRC project number 304191 - ENERGIX) and from the Ministry of Science and Technology of China (MOST project number 2019YFE0104900).

List Of Captions:

Table 1. Summary of building energy model calibration approaches and research gap

Table 2. Opaque Surface Cooling Factor Coefficients [40]

Table 3. Envelope Properties of Case Study

Table 4. External Walls and Roof Construction and Parameters

Table 5. Glazing Construction and Parameters

Table 6. Case Study HVAC Components

Table 7 . Zone HVAC Attributes

Table 8. Calibrated Infiltration and SHGC for The Case Study

Fig. 1. Opaque Load Sensitive Factor (C-opq)

Fig. 2. Information flow for the proposed TNDC technique

Fig. 3.

Fig. 4. Case Study Building

Fig. 5. Case Study HVAC Model

Fig. 6. Actual and Pre-Calibrated Cooling Gas Use (27th July – 6th August)

Fig. 7. CV(RSME) versus air infiltration rate

Fig. 8. Duration Curves for Nighttime Gas Use from 27th July to 6th August

Fig. 9. Duration Curves for Daytime Gas Use from 27th July to 6th August

Fig. 10. CV(RSME) versus SHGC

Fig. 11. Duration Curve for the entire day gas use

Fig. 12. Measured and Simulated Gas Use from 27th July to 6th August

Fig. 13. Heat Gain from Windows, Opaque Surfaces, and Air Infiltration on a Typical Day July (23rd July)

Fig. 14. Simulated and Actual Gas Use for a) 21st July Weekday and b) 24th July Weekend

Fig. 15. Simulated and Actual Cooling Gas Use for Summer Months

Fig. 16. False Ceiling Air Ways to the Exterior.

Fig. 17. a) Air ways to false ceiling, b) isolation after the retrofit

Table 1. Summary of building energy model calibration approaches and research gap

Data resolution	Calibration method	Key calibrated parameters	Main contribution	Identified research gap	Ref
Hourly	Surrogate modeling + neural networks	Envelope and system parameters	Development of a surrogate NN-based framework to accelerate BEM calibration	Lacks physical interpretability of calibrated parameters and does not distinguish day/night effects	[31]
Monthly / Hourly	Bayesian inference	Multiple uncertain model parameters	Open-source Bayesian platform for probabilistic BEM calibration	Computationally intensive and does not target physical identifiability of key cooling-related parameters	[32]
Hourly	Simulation-based calibration	HVAC and envelope parameters	Calibration of BEMs for multi-unit NZEB buildings	Parameters calibrated in an aggregated manner; no explicit temporal (day/night) separation	[34]
Monthly / Hourly	Simplified calibrated models	Reduced parameter set	Use of minimally calibrated models for retrofit performance prediction	Limited capability to reproduce hourly cooling dynamics	[36]
Hourly	Comparative validation	Air infiltration	Assessment of infiltration impact on calibration accuracy	Infiltration treated as a time-invariant parameter without diurnal sensitivity	[38]
Monthly	Automatic calibration	Envelope and system parameters	Automated calibration of prototype BEMs for retrofit analysis	Insufficient resolution for accurate hourly cooling load representation	[37]
Hourly	Sensitivity-based calibration	Infiltration, SHGC	Investigation of modeling complexity versus calibration accuracy	No operational framework for temporal separation of parameter sensitivity	[39]
Hourly	Multi-variable calibration	Solar and thermal properties	Integration of air and surface temperatures in calibration	Focuses on numerical accuracy rather than physical parameter identifiability	[35]
Hourly (high-resolution)	Bayesian + deep learning	Multiple envelope parameters	High-resolution calibration accounting for uncertainty	Method complexity limits transparency and practical engineering application	[33]

Table 2. Opaque Surface Cooling Factor Coefficients [40]

Surface Type	OF _t	OF _b - K	OF _r
Ceiling or wall adjacent to vented attic	0.62	14.3α - 4.5	-0.19
Ceiling/roof assembly	1	38.3α - 7	-0.36
Wall (wood frame) or door with solar exposure	1	8.2	-0.36
Wall (wood frame) or door (shaded)	1	0	-0.36
Floor over ambient	1	0	-0.06
Floor over crawlspace	0.33	0	-0.28

Table 3. Envelope Properties of Case Study

	North	East	South	West	Total
Wall Area [m ²]	1216	1248	1216	1248	4928
Window Fenestration Area [m ²]	598.4	374.7	598.4	160	1731
Window-to-Wall Ratio [%]	49.21	30.02	49.21	12.82	35.12
Gross Roof Area [m ²]					1314

Table 4. External Walls and Roof Construction and Parameters

Construction	layers	Thermal Conductivity [W/(m.K)]	Density [kg/m ³]	Specific Heat [J/(kg.K)]	Overall U-value [W/m ² .K]
External wall	Brick-fired clay - 2400 kg/m ³ - 102mm	1.34	2400	790	0.84
	Concrete HW 200mm	1.7	2243	837	
	Wall Insulation 50mm	0.08	91	837	
	Gypsum 12.5mm	0.16	785	830	
Roof	Roof Membrane 9.5 mm	0.16	1121	1460	1.217
	Roof Insulation 500 mm	0.08	256	836	
	Metal Decking 1.5 mm	45	7680	418	

Table 5. Glazing Construction and Parameters

Glazing	Construction	U-value [W/m ² .K]	SHGC (Initial estimate)
Exterior Window	2× GREY 6mm+ Air 6mm	2.6	0.2
West Glass Wall	Clear Glass Block	5.5	0.2
Sky Roof	GREY 12mm	5.5	0.2

Table 6. Case Study HVAC Components

Item	ID	Capacity	Unit	Type
Chiller	-	100	RT	Unicold JAR-100-DS
Fan Coil	FC	2000	CFM	TAHVIEH TFD-TB-3400
AHU	T1	5000	CFM	SARAVEL-MLZ-500
AHU	T2	7000	CFM	SARAVEL-MLZ-700
AHU	T3	10000	CFM	SARAVEL-MLZ-1000

Table 7 . Zone HVAC Attributes

Zone No.	Zone Name	Area (m ²)	Volume (m ³)	HVAC Component (No.* ID)
1	Amphitheater	252	1512	1*T2
2	Corridors	208*5	624*5	10*FC
3	Engine Room	359	1077	Unconditioned
4	Lab	359	1077	1*T2
5	North 1-2	359*2	1077*2	1*T3
6	North-GF	359	1077	1*T2
7	North 3	359	1077	1*T1
8	South 1-2	359*2	1077*2	1*T3
9	South-GF	359	1077	1*T2
10	South 3	359	1077	1*T1
11	Library	252	1008	1*T2
12	Stairs	24*5	480	Unconditioned
13	WC-AHU	56*10	168*10	Unconditioned
14	Plenum	1038*5	1038*5	not part of total
Conditioned Total		4775	15333	

455

Table 8. *Calibrated Infiltration and SHGC for The Case Study*

	Case Study	Baseline Ref: [53], [54]	Green standard Ref: [28,31]
Whole Case Study Air Leakage Rates (lit/s/m ²) (75 Pa)	21.3	9.14	2
Whole Case Study Air Leakage (ACH) (normal pressure)	3.2	1.4	0.3
SHGC	0.8	0.5	0.19-0.5

456

457

Accepted by Scientia Iranica

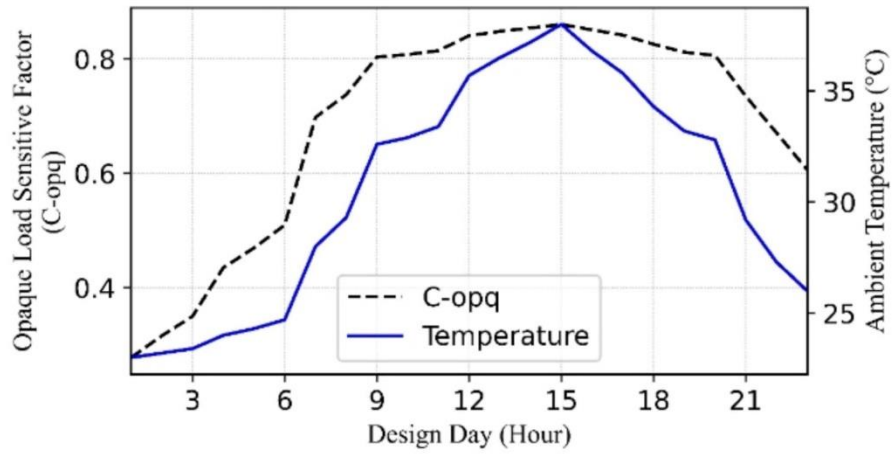


Fig. 1. Opaque Load Sensitive Factor (C-opq)

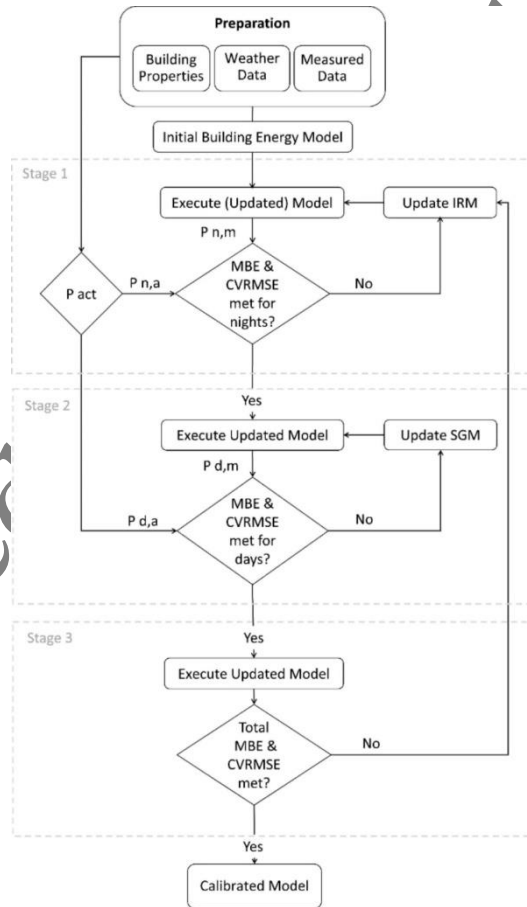


Fig. 2. Information flow for the proposed TNDC technique

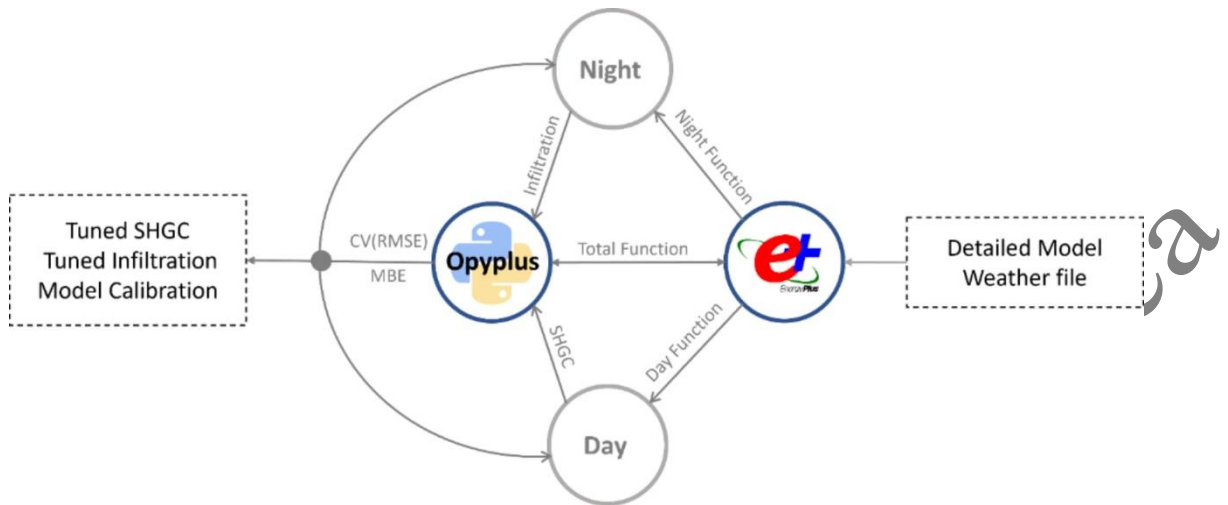


Fig. 3. Python–EnergyPlus TNDC workflow for Infiltration and SHGC

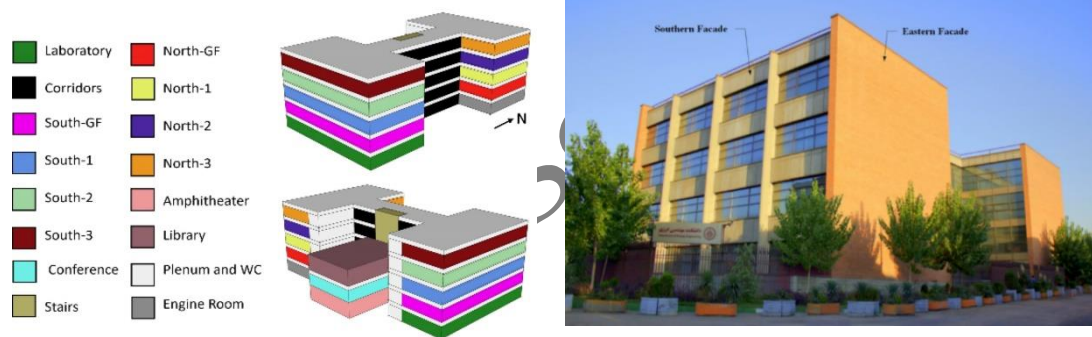
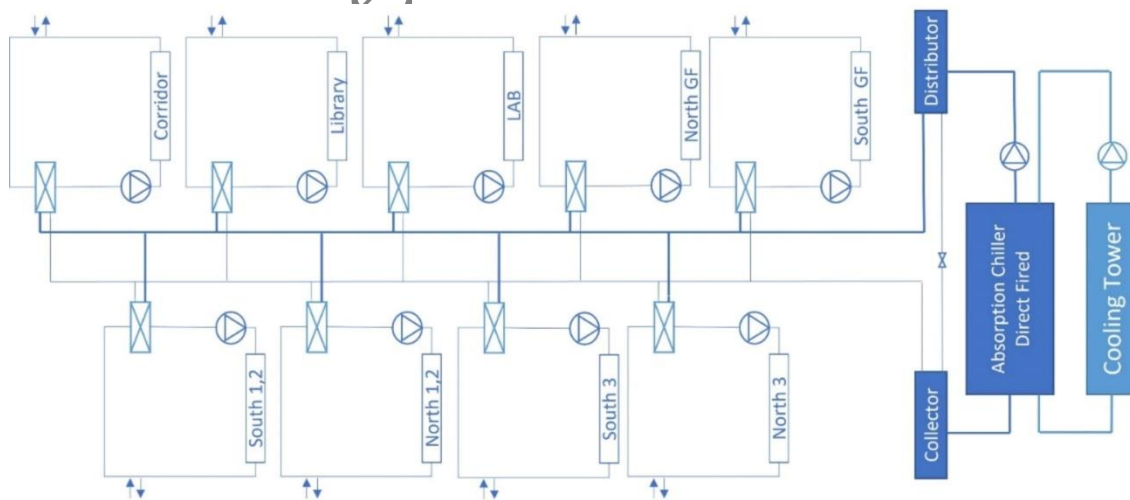
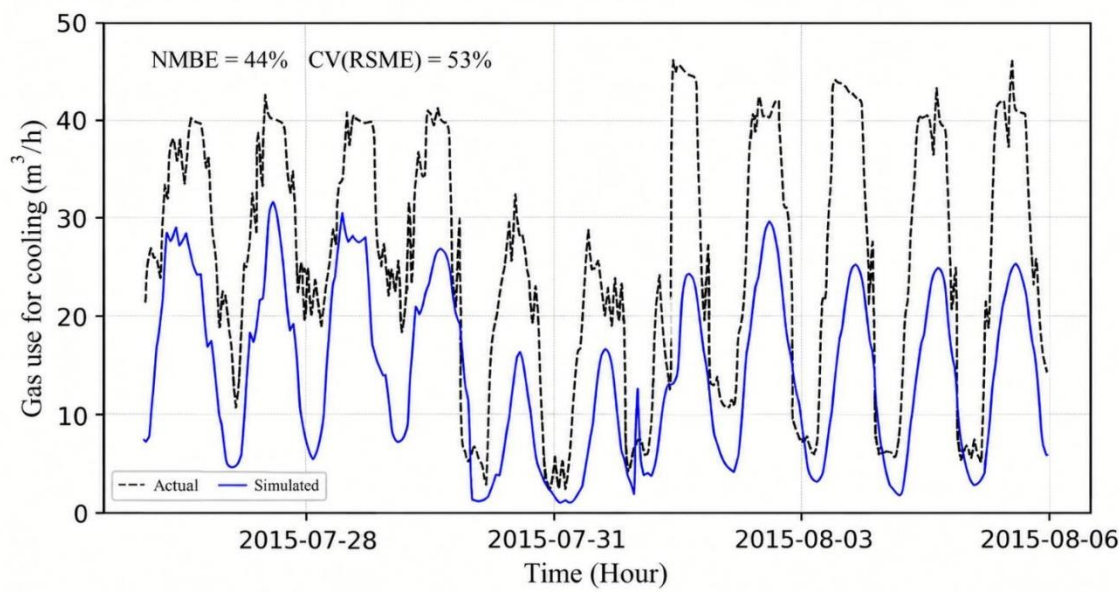


Fig. 4. Case Study Building



467

Fig. 5. Case Study HVAC Model

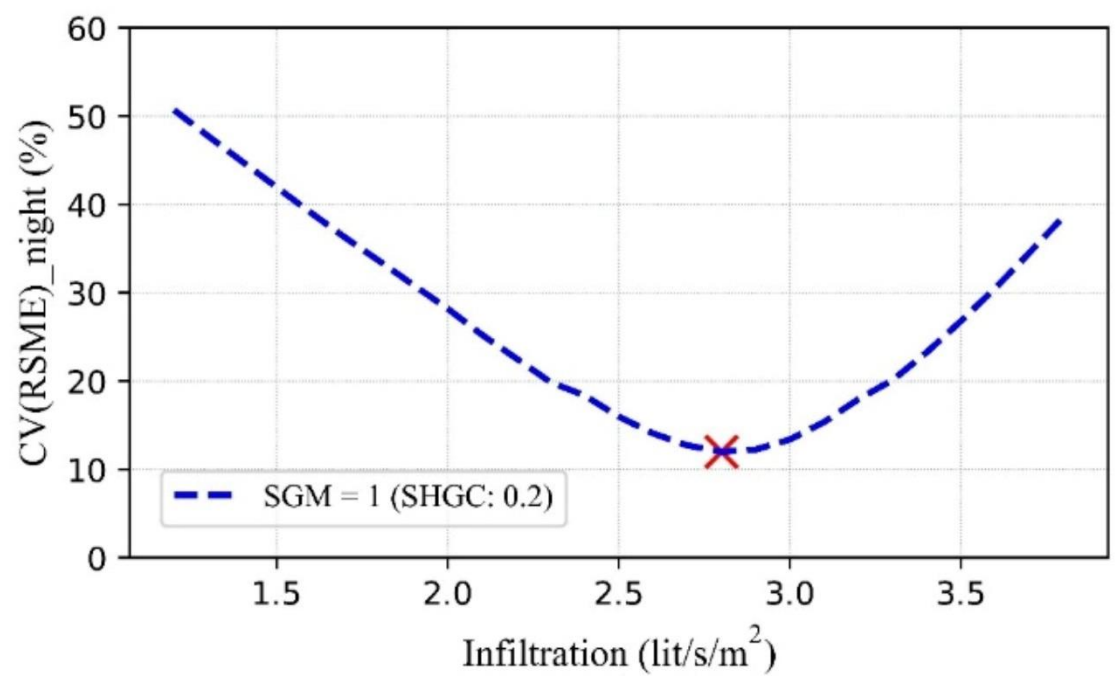


468

469

Fig. 6. Actual and Pre-Calibrated Cooling Gas Use (27th July – 6th August)

470



471

472

Fig. 7. CV(RSME) versus air infiltration rate

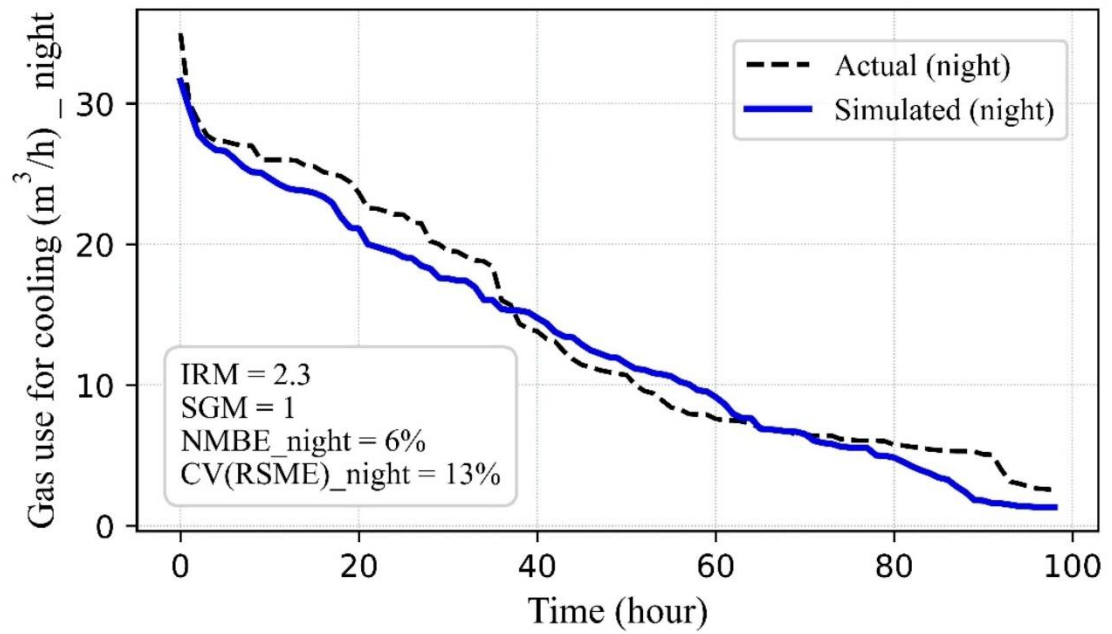


Fig. 8. Duration Curves for Nighttime Gas Use from 27th July to 6th August

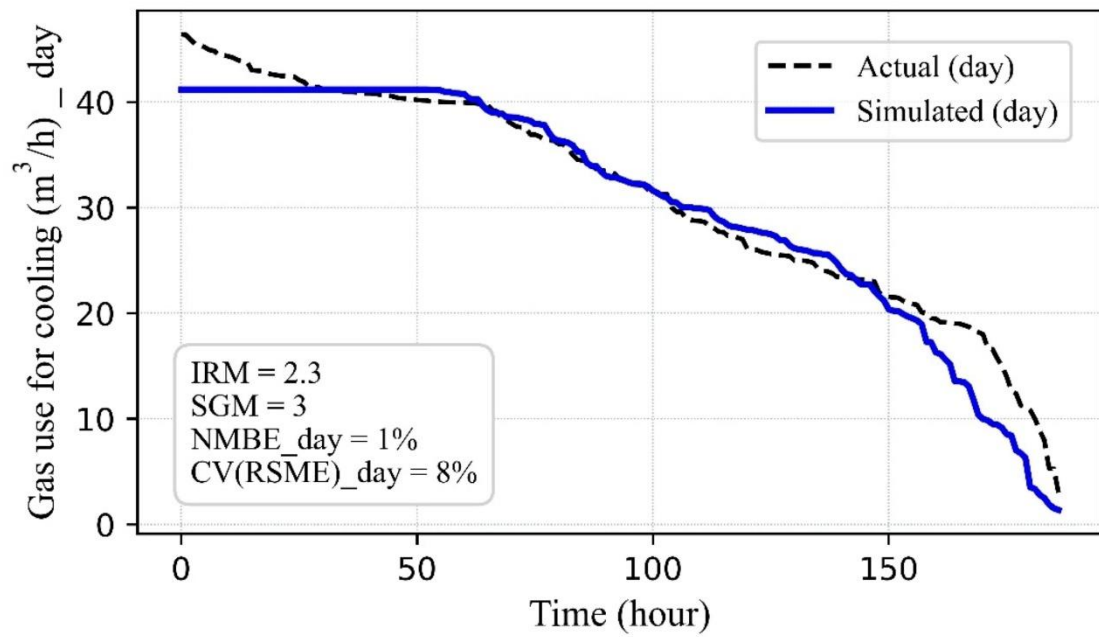


Fig. 9. Duration Curves for Daytime Gas Use from 27th July to 6th August

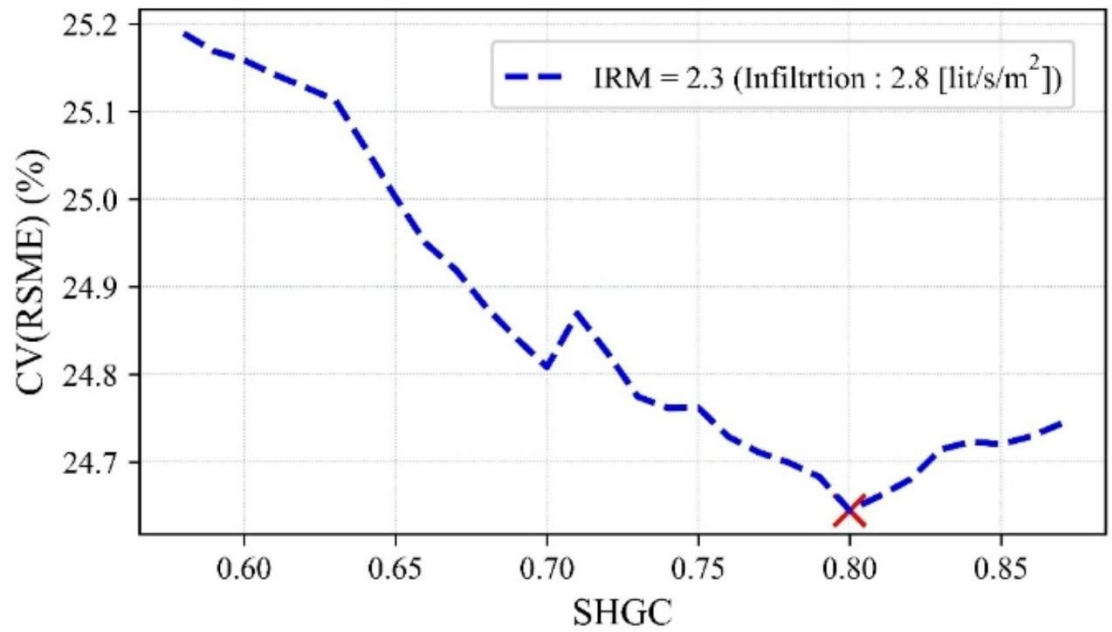


Fig. 10. CV(RSME) versus SHGC

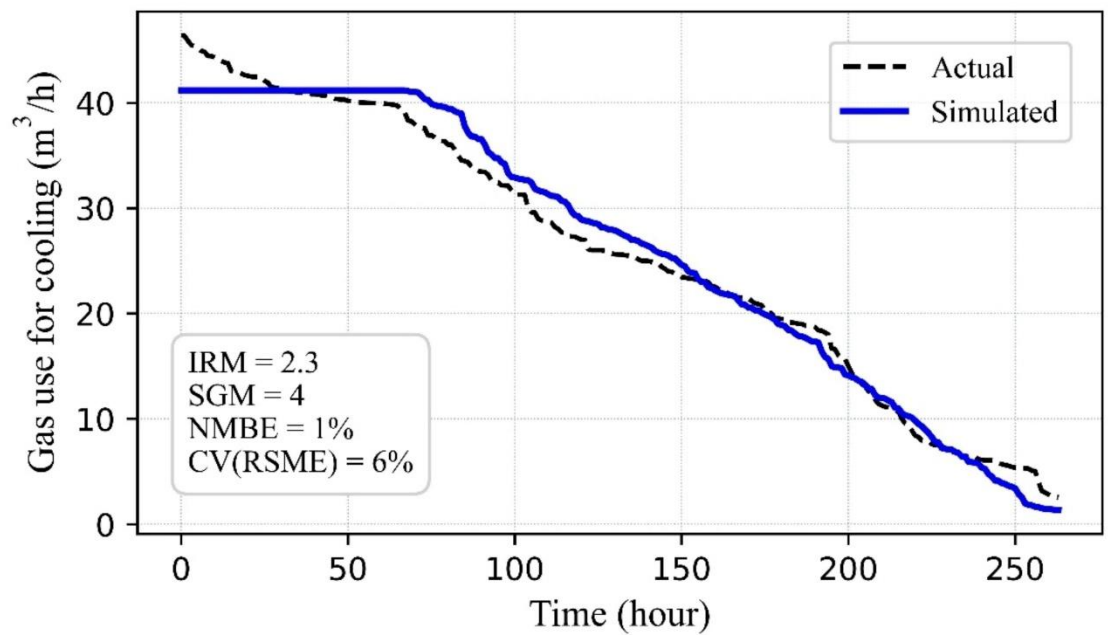


Fig. 11. Duration Curve for the entire day gas use

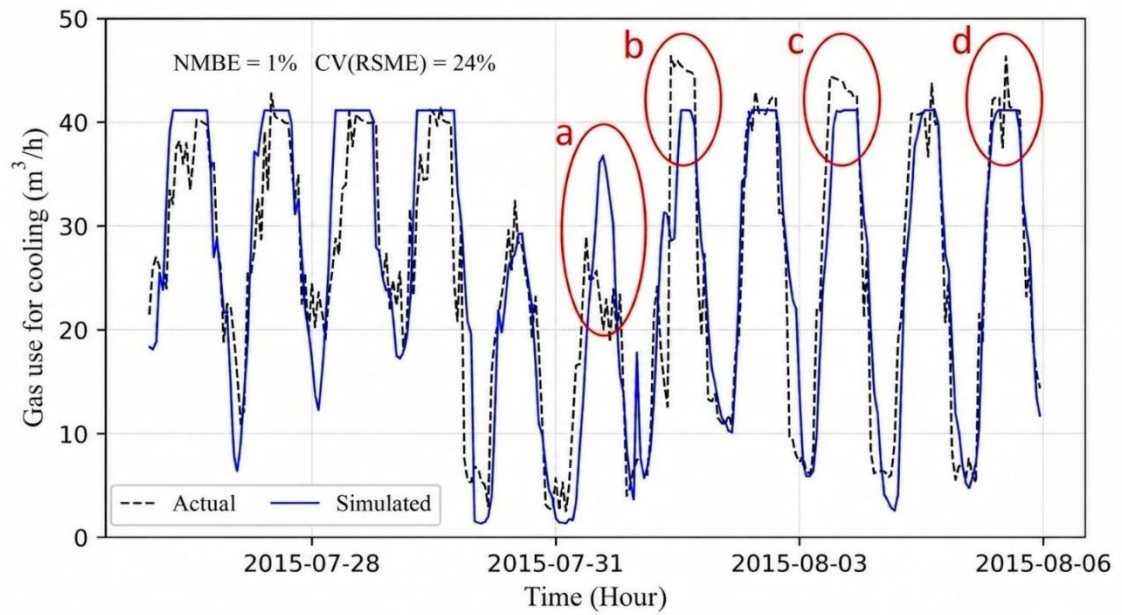


Fig. 12. Measured and Simulated Gas Use from 27th July to 6th August

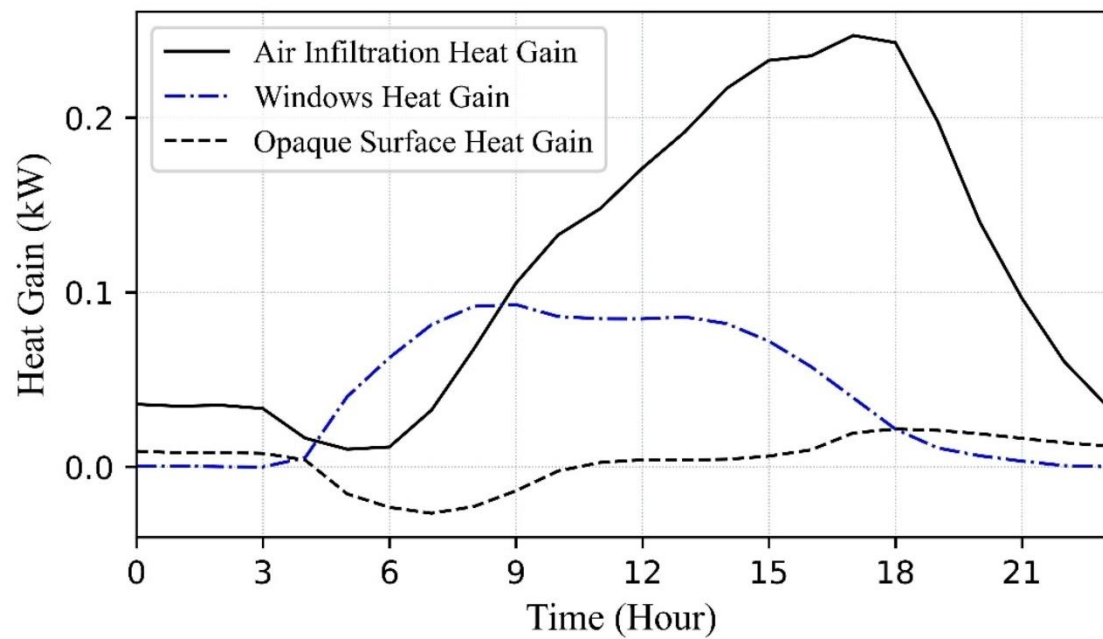
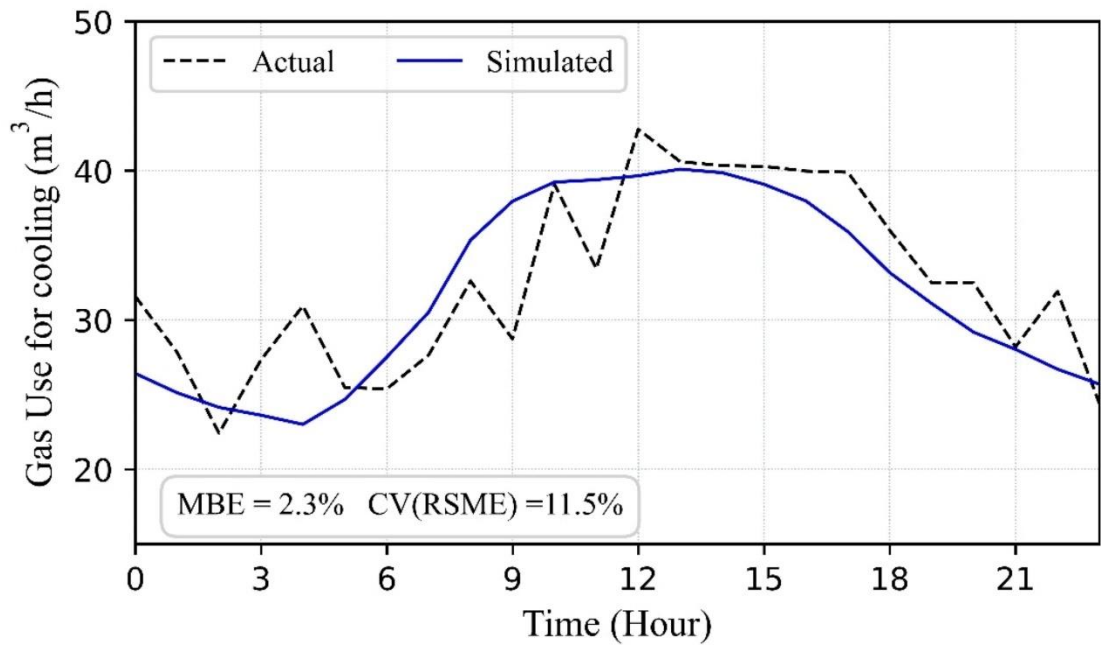
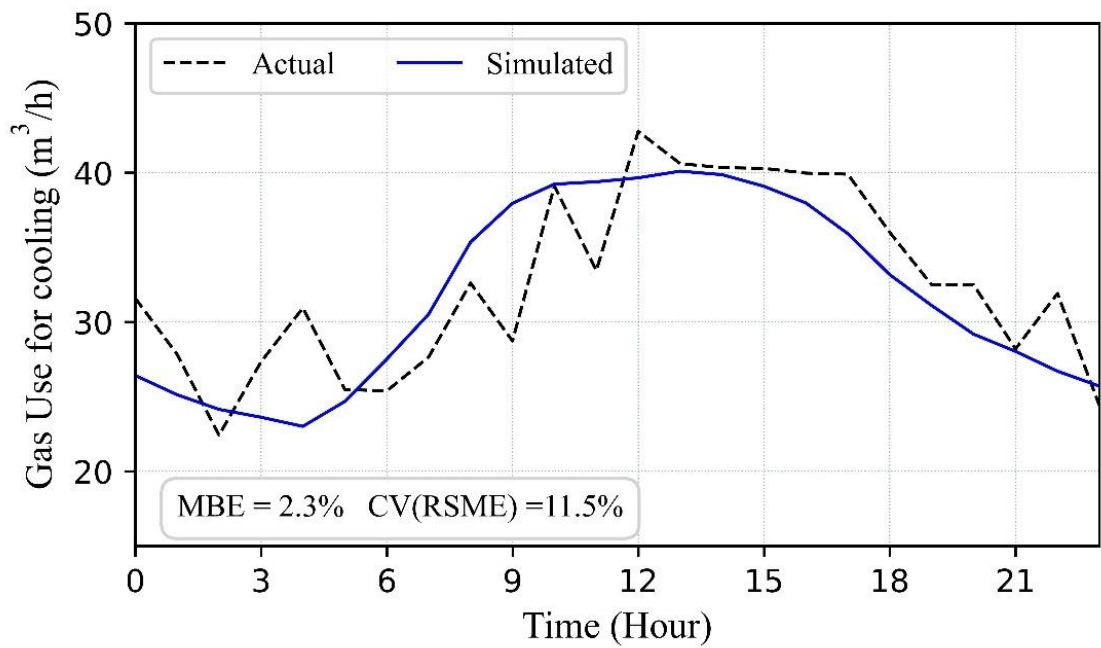


Fig. 13. Heat Gain from Windows, Opaque Surfaces, and Air Infiltration on a Typical Day July (23rd July)



a).



b)

Fig. 14. Simulated and Actual Gas Use for a) 21st July Weekday and b) 24th July Weekend

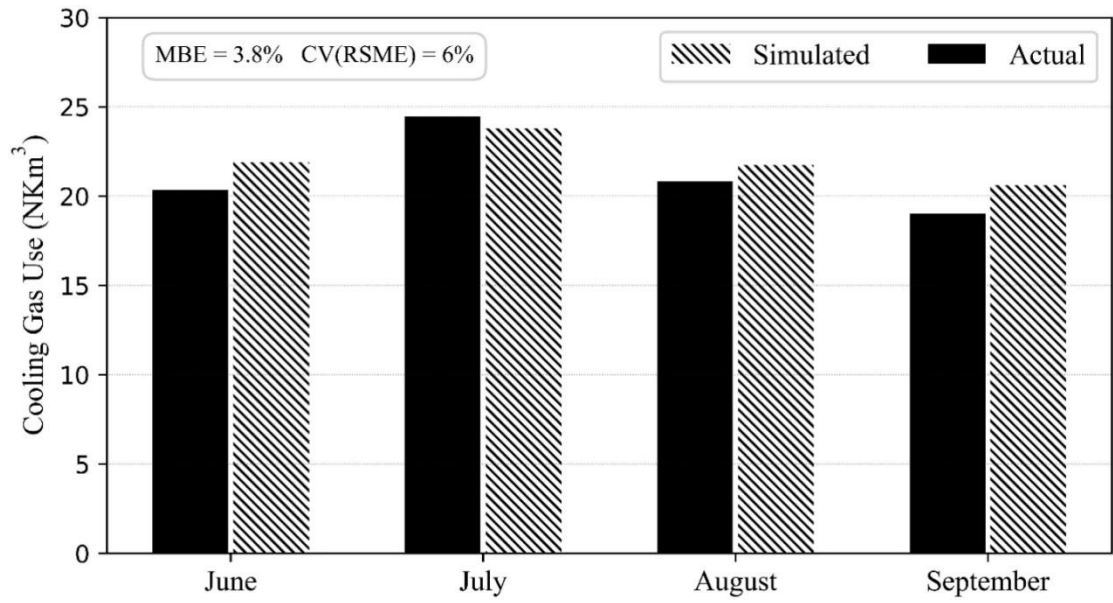


Fig. 15. Simulated and Actual Cooling Gas Use for Summer Months

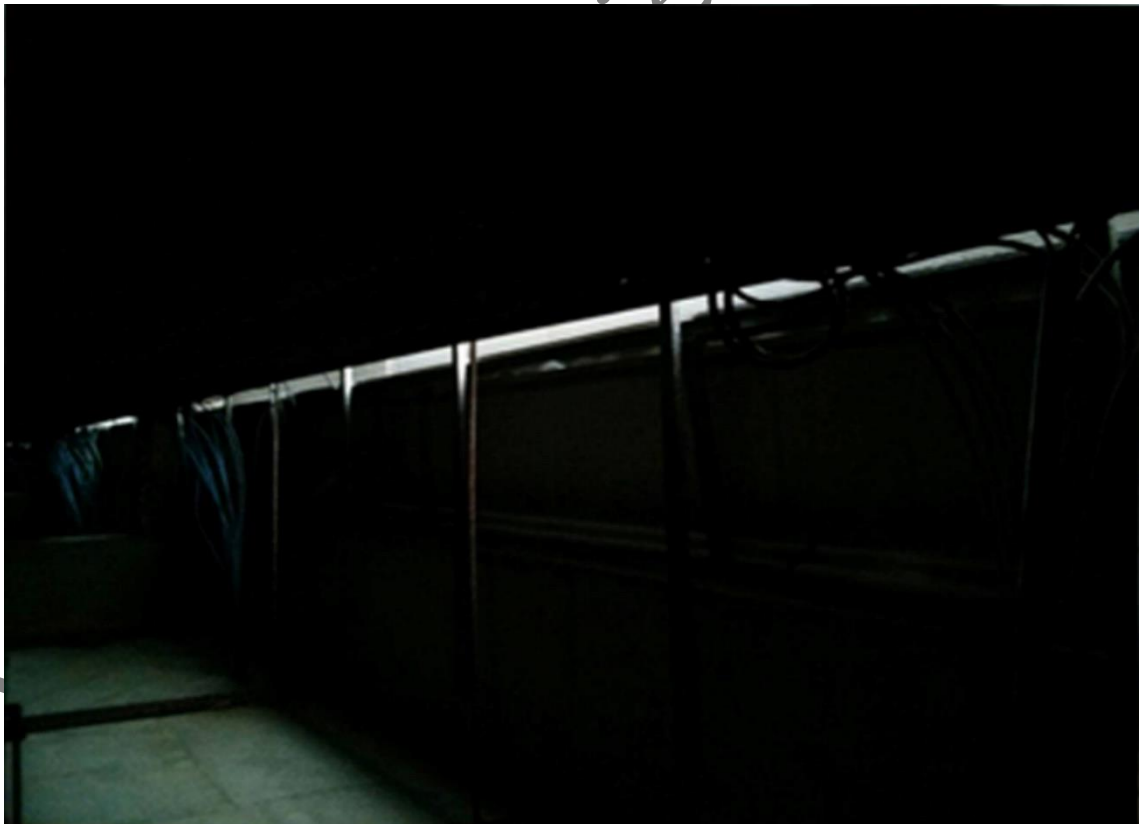


Fig. 16. False Ceiling Air Ways to the Exterior.



a)

b)

Fig. 17. a) Air ways to false ceiling, b) isolation after the retrofit

References

- [1] Y. Huang and J. L. Niu, "Optimal building envelope design based on simulated performance: History, current status and new potentials," *Energy Build.*, vol. 117, pp. 387–398, Apr. 2016, [doi: 10.1016/J.ENBUILD.2015.09.025](https://doi.org/10.1016/J.ENBUILD.2015.09.025).
- [2] X. Zhong, M. Hu, S. Deetman, et al., "Global greenhouse gas emissions from residential and commercial building materials and mitigation strategies to 2060," *Nat. Commun.*, vol. 12, no. 1, p. 6126, 2021, [doi: 10.1038/s41467-021-26212-z](https://doi.org/10.1038/s41467-021-26212-z).
- [3] M. Santamouris and D. Kolokotsa, "Passive cooling dissipation techniques for buildings and other structures: The state of the art," *Energy Build.*, vol. 57, pp. 74–94, Feb. 2013, [doi: 10.1016/J.ENBUILD.2012.11.002](https://doi.org/10.1016/J.ENBUILD.2012.11.002).
- [4] A. Prieto, U. Knaack, T. Klein, et al., "25 Years of cooling research in office buildings: Review for the integration of cooling strategies into the building façade (1990–2014)," *Renew. Sustain. Energy Rev.*, vol. 71, pp. 89–102, May 2017, [doi: 10.1016/J.RSER.2017.01.012](https://doi.org/10.1016/J.RSER.2017.01.012).
- [5] J. Niu, Z. Tian, Y. Lu, et al., "A robust optimization model for designing the building cooling source under cooling load uncertainty," *Appl. Energy*, vol. 241, pp. 390–403, May 2019, [doi: 10.1016/J.APENERGY.2019.03.062](https://doi.org/10.1016/J.APENERGY.2019.03.062).
- [6] A. Chong, Y. Gu, and H. Jia, "Calibrating building energy simulation models: A review of the basics to guide future work," *Energy Build.*, vol. 253, p. 111533, Dec. 2021, [doi: 10.1016/J.ENBUILD.2021.111533](https://doi.org/10.1016/J.ENBUILD.2021.111533).
- [7] M. Ahmad and C. H. Culp, "Uncalibrated building energy simulation modeling results," *HVAC R Res.*, vol. 12, no. 4, pp. 1141–1155, 2006, [doi: 10.1080/10789669.2006.10391455](https://doi.org/10.1080/10789669.2006.10391455).
- [8] Z. Yang and B. Becerik-Gerber, "A model calibration framework for simultaneous multi-level building energy simulation," *Appl. Energy*, vol. 149, pp. 415–431, Jul. 2015, [doi: 10.1016/J.APENERGY.2015.03.048](https://doi.org/10.1016/J.APENERGY.2015.03.048).
- [9] S. Asadi, E. Mostavi, D. Boussaa, et al., "Building energy model calibration using automated optimization-based algorithm," *Energy Build.*, vol. 198, pp. 106–114, Sep. 2019, [doi: 10.1016/J.ENBUILD.2019.06.001](https://doi.org/10.1016/J.ENBUILD.2019.06.001).
- [10] P. Raftery, M. Keane, and A. Costa, "Calibrating whole building energy models: Detailed case study using hourly measured data," *Energy Build.*, vol. 43, no. 12, pp. 3666–3679, Dec. 2011, [doi: 10.1016/j.enbuild.2011.09.039](https://doi.org/10.1016/j.enbuild.2011.09.039).
- [11] G. Mustafaraj, D. Marini, A. Costa, et al., "Model calibration for building energy efficiency simulation," *Appl. Energy*, vol. 130, pp. 72–85, Oct. 2014, [doi: 10.1016/J.APENERGY.2014.05.019](https://doi.org/10.1016/J.APENERGY.2014.05.019).
- [12] Y.-S. Kim, M. Heidarinejad, M. Dahlhausen, et al., "Building energy model calibration with schedules derived from electricity use data," *Appl. Energy*, vol. 190, pp. 997–1007, Mar. 2017, [doi: 10.1016/J.APENERGY.2016.12.167](https://doi.org/10.1016/J.APENERGY.2016.12.167).
- [13] O. Vera-Piazzini and M. Scarpa, "Building energy model calibration: A review of the state of the art in approaches, methods, and tools," *J. Build. Eng.*, vol. 86, p. 108287, Jun. 2024, [doi: 10.1016/J.JOBE.2023.108287](https://doi.org/10.1016/J.JOBE.2023.108287).
- [14] N. Johnson, "Building Energy Model Calibration for Retrofit Decision Making," Portland, OR, Jan. 2000.
- [15] S. Zuhaib, M. Hajdukiewicz, and J. Goggins, "Application of a staged automated calibration methodology to a partially-retrofitted university building energy model," *J. Build. Eng.*, vol. 26, p. 100866, Nov. 2019, [doi: 10.1016/J.JOBE.2019.100866](https://doi.org/10.1016/J.JOBE.2019.100866).
- [16] Y. Heo, R. Choudhary, and G. A. Augenbroe, "Calibration of building energy models for retrofit analysis under uncertainty," *Energy Build.*, vol. 47, pp. 550–560, Apr. 2012, [doi: 10.1016/J.ENBUILD.2011.12.029](https://doi.org/10.1016/J.ENBUILD.2011.12.029).
- [17] K. Sun, T. Hong, S. C. Taylor-Lange, et al., "A pattern-based automated approach to building energy model calibration,"

- 540 *Appl. Energy*, vol. 165, pp. 214–224, Mar. 2016, [doi: 10.1016/j.apenergy.2015.12.026](https://doi.org/10.1016/j.apenergy.2015.12.026).
- 541 [18] V. G. González and C. F. Bandera, “A building energy models calibration methodology based on inverse modelling
542 approach,” *Build. Simul.*, vol. 15, no. 11, pp. 1883–1898, 2022, [doi: 10.1007/s12273-022-0900-5](https://doi.org/10.1007/s12273-022-0900-5).
- 543 [19] M. Derakhti, W. O’Brien, and S. Bucking, “Impact of measured data frequency on commercial building energy model
544 calibration for retrofit analysis,” *Sci. Technol. Built Environ.*, vol. 28, no. 5, pp. 628–644, May 2022, [doi:
545 10.1080/23744731.2021.1991177](https://doi.org/10.1080/23744731.2021.1991177).
- 546 [20] G. Liu and M. Liu, “A rapid calibration procedure and case study for simplified simulation models of commonly used
547 HVAC systems,” *Build. Environ.*, vol. 46, no. 2, pp. 409–420, Feb. 2011, [doi: 10.1016/J.BUILDENV.2010.08.002](https://doi.org/10.1016/J.BUILDENV.2010.08.002).
- 548 [21] D. Coakley, P. Raftery, and M. Keane, “A review of methods to match building energy simulation models to measured
549 data,” *Renew. Sustain. Energy Rev.*, vol. 37, pp. 123–141, Sep. 2014, [doi: 10.1016/J.RSER.2014.05.007](https://doi.org/10.1016/J.RSER.2014.05.007).
- 550 [22] F. Roberti, U. F. Oberegger, and A. Gasparella, “Calibrating historic building energy models to hourly indoor air and
551 surface temperatures: Methodology and case study,” *Energy Build.*, vol. 108, pp. 236–243, Dec. 2015, [doi:
552 10.1016/j.enbuild.2015.09.010](https://doi.org/10.1016/j.enbuild.2015.09.010).
- 553 [23] G. Han, J. Srebric, and E. Enache-Pommer, “Different modeling strategies of infiltration rates for an office building to
554 improve accuracy of building energy simulations,” *Energy Build.*, vol. 86, pp. 288–295, Jan. 2015, [doi:
555 10.1016/J.ENBUILD.2014.10.028](https://doi.org/10.1016/J.ENBUILD.2014.10.028).
- 556 [24] A. Dutta and A. Samanta, “Reducing cooling load of buildings in the tropical climate through window glazing: A model
557 to model comparison,” *J. Build. Eng.*, vol. 15, pp. 318–327, Jan. 2018, [doi: 10.1016/J.JOBE.2017.12.005](https://doi.org/10.1016/J.JOBE.2017.12.005).
- 558 [25] Y. Yildiz, K. Korkmaz, T. Göksal özbalta, et al., “An approach for developing sensitive design parameter guidelines to
559 reduce the energy requirements of low-rise apartment buildings,” *Appl. Energy*, vol. 93, pp. 337–347, May 2012, [doi:
560 10.1016/J.APENERGY.2011.12.048](https://doi.org/10.1016/J.APENERGY.2011.12.048).
- 561 [26] J. Feijó-Muñoz, C. Pardal, V. Echarri, et al., “Energy impact of the air infiltration in residential buildings in the
562 Mediterranean area of Spain and the Canary islands,” *Energy Build.*, vol. 188–189, pp. 226–238, Apr. 2019, [doi:
563 10.1016/J.ENBUILD.2019.02.023](https://doi.org/10.1016/J.ENBUILD.2019.02.023).
- 564 [27] J. Hu, Z. Liu, G. Ma, et al., “Air infiltration and related building energy consumption: A case study of office buildings
565 in Changsha, China,” *J. Build. Eng.*, vol. 74, p. 106859, Sep. 2023, [doi: 10.1016/J.JOBE.2023.106859](https://doi.org/10.1016/J.JOBE.2023.106859).
- 566 [28] International Code Council (ICC). *International Green Construction Code (IgCC)*, 2024 Edition. Washington, DC: ICC,
567 2024.
- 568 [29] ANSI/ASHRAE/IES 90.1-2022. *Energy Standard for Sites and Buildings Except Low-Rise Residential Buildings*.
569 Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), 2023.
- 570 [30] “Standard for the Design of High-Performance Green Buildings,” *Ashrae 189.1*, 2017.
- 571 [31] E. Herbing, C. Vanden Hof, and M. Kummert, “Building energy model calibration using a surrogate neural network,”
572 *Energy Build.*, vol. 289, p. 113057, Jun. 2023, [doi: 10.1016/J.ENBUILD.2023.113057](https://doi.org/10.1016/J.ENBUILD.2023.113057).
- 573 [32] D. Hou, D. Zhan, L. Wang, et al., “Development and performance assessment of a new opensource Bayesian inference
574 R platform for building energy model calibration,” *Discov. Mech. Eng.*, vol. 2, no. 1, p. 19, 2023, [doi: 10.1007/s44245-
575 023-00027-2](https://doi.org/10.1007/s44245-023-00027-2).
- 576 [33] G. Jiang, Y. Chen, Z. Wang, et al., “A deep learning-based Bayesian framework for high-resolution calibration of
577 building energy models,” *Energy Build.*, vol. 323, p. 114755, Nov. 2024, [doi: 10.1016/J.ENBUILD.2024.114755](https://doi.org/10.1016/J.ENBUILD.2024.114755).

- [34] F. Ochs, N. Franzoi, G. Dermentzis, et al., "Monitoring and simulation-based optimization of two multi-apartment NZEBs with heat pump, solar thermal and PV," *J. Build. Perform. Simul.*, vol. 17, no. 1, pp. 1–26, Jan. 2024, doi: [10.1080/19401493.2023.2227605](https://doi.org/10.1080/19401493.2023.2227605).
- [35] M. C. Demarchi, S. Gervaz Canessa, G. Pena, et al., "Enhancing the Accuracy of Thermal Model Calibration: Integrating Zone Air and Surface Temperatures, Convection Coefficients, and Solar and Thermal Absorptivity," *Energy Build.*, vol. 336, p. 115617, Jun. 2025, doi: [10.1016/J.ENBUILD.2025.115617](https://doi.org/10.1016/J.ENBUILD.2025.115617).
- [36] A. Carratt, G. Kokogiannakis, and D. Daly, "Using calibrated minimum input models to predict retrofit performance on residential dwellings," *J. Build. Perform. Simul.*, vol. 18, no. 1, pp. 39–55, Jan. 2025, doi: [10.1080/19401493.2024.2419933](https://doi.org/10.1080/19401493.2024.2419933).
- [37] Y. Chen, W. Wei, C. Song, et al., "Rapid Building Energy Modeling Using Prototype Model and Automatic Model Calibration for Retrofit Analysis with Uncertainty," *Buildings*, vol. 13, no. 6, p. 1427, 2023, doi: [10.3390/buildings13061427](https://doi.org/10.3390/buildings13061427).
- [38] G. Bastos Porsani, J. B. Echeverría Trueba, and C. Fernández Bandera, "Triple Validation of Calibrated Building Energy Models with Different Air Infiltration Values," *Applied Sciences*, vol. 14, no. 23, p. 10828, 2024, doi: [10.3390/app142310828](https://doi.org/10.3390/app142310828).
- [39] L. Peinturier and D. C. H. Wallom, "Building energy simulation calibration accuracy and modelling complexity: Implications for energy performance improvement," *Energy Build.*, vol. 344, p. 115971, Oct. 2025, doi: [10.1016/J.ENBUILD.2025.115971](https://doi.org/10.1016/J.ENBUILD.2025.115971).
- [40] American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), *ASHRAE Handbook—Fundamentals*, 2021 ed. Atlanta, GA, USA: ASHRAE, 2021.
- [41] M. Sherman and D. Grimsrud, "Infiltration-pressurization correlation: Simplified physical modeling," *ASHRAE Trans.*, vol. 86, Jan. 1980.
- [42] J. Parasonis, A. Kezikas, and D. Kalibatiene, "The relationship between the shape of a building and its energy performance," *Archit. Eng. Des. Manag.*, vol. 8, pp. 1–11, Jan. 2011, doi: [10.1080/17452007.2012.675139](https://doi.org/10.1080/17452007.2012.675139).
- [43] A. G. ASHRAE, "Guideline 14-2014: Measurement of energy, demand, and water savings," *Am. Soc. heating, Refrig. air Cond. Eng. Atlanta, Georg.*, 2014.
- [44] "EVO. International performance measurement & verification protocol. Efficiency Valuation Organisation; 2007." [Online]. Available: <https://evo-world.org/en/products-services-mainmenu-en/protocols/ipmvp>.
- [45] M. J. Kaiser and A. G. Pulsipher, "Preliminary assessment of the Louisiana Home Energy Rebate Offer program using IPMVP guidelines," *Appl. Energy*, vol. 87, no. 2, pp. 691–702, Feb. 2010, doi: [10.1016/j.apenergy.2009.08.001](https://doi.org/10.1016/j.apenergy.2009.08.001).
- [46] J. P. Waltz, "Measuring and Verifying Your Energy Performance Contracts...: What are Your Options? How do You Choose?," *Strateg. Plan. Energy Environ.*, vol. 21, no. 4, pp. 47–64, Apr. 2002, doi: [10.1080/10485230209509595](https://doi.org/10.1080/10485230209509595).
- [47] S. Ginestet, D. Marchio, and O. Morisot, "Improvement of buildings energy efficiency: Comparison, operability and results of commissioning tools," *Energy Convers. Manag.*, vol. 76, pp. 368–376, Dec. 2013, doi: [10.1016/J.ENCONMAN.2013.07.057](https://doi.org/10.1016/J.ENCONMAN.2013.07.057).
- [48] I. El-Darwish and M. Gomaa, "Retrofitting strategy for building envelopes to achieve energy efficiency," *Alexandria Eng. J.*, vol. 56, no. 4, pp. 579–589, Dec. 2017, doi: [10.1016/J.AEJ.2017.05.011](https://doi.org/10.1016/J.AEJ.2017.05.011).
- [49] Openenergy Development Team, *opyplus: Python package to work with EnergyPlus input and output*, Version 2.0.7, 2024. [Software]. Available: opyplus PyPI.

- 617 [50] A. Tabadkani, M. Haddadi, R. A. Rizi, et al., "A hierarchical multi-purpose roller shade controller to enhance indoor
618 comfort and energy efficiency," *Build. Simul.*, vol. 16, no. 7, pp. 1239–1256, 2023, doi: 10.1007/s12273-023-1003-7.
- 619 [51] M. Haddadi and A. Rajabi, "TNDC Calibration Technique V1 Available at: [http://www.github.com/TNDC-](http://www.github.com/TNDC-Calibration)
620 [Calibration](http://www.github.com/TNDC-Calibration)," 2024.
- 621 [52] "National building code, part 19, 'saving energy' Iran Building and Housing Research Center," 1399.
- 622 [53] *ASHRAE 90.1 (2004): Energy Standard for Buildings Except Low-Rise Residential Buildings : American Society of*
623 *Heating, Refrigerating and Air Conditioning Engineers*. 2004.
- 624 [54] K. Gowri, D. W. Winiarski, and R. E. Jarnagin, "Infiltration modeling guidelines for commercial building energy
625 analysis," Sep. 2009, doi: 10.2172/968203.
- 626 [55] "Tehran Weather Data Available at I.R.OF IRAN Meteorological Organization ;," 2024. [Online]. Available:
627 <http://www.irimo.ir/eng/index.php>.
- 628 [56] "Tehran EnergyPlus Weather File (epw) Available at:," 2024. [Online]. Available: <https://energyplus.net/weather>.

629

630 Biographies

631 **Morteza Haddadi** is a PhD student in Energy Systems Engineering at Sharif University of Technology, Iran. His research
632 interests include building energy performance, energy efficiency, building energy simulation, and sustainable energy systems.
633 He conducted a research sabbatical at the Norwegian University of Science and Technology (NTNU), Norway, under the
634 supervision of Professor Natasa Nord.

635 **Abbas Rajabi-Ghahnavieh** is an energy system and IoT engineer and a faculty member in the Department of Energy
636 Engineering at Sharif University of Technology, Iran. He currently serves as the Head of the Sharif Energy, Water and
637 Environment Research Institute. His research interests include energy networks, IoT, smart cities, and the Internet of Energy.

638 **Natasa Nord** is a Professor at the Department of Energy and Process Engineering at the Norwegian University of Science and
639 Technology (NTNU), Norway. Her research focuses on building energy systems, energy efficiency, building performance
640 simulation, HVAC systems, district heating and cooling, zero-emission buildings, energy analysis, and sustainable energy
641 system development.