Integrating Latent Load into the Cooling Degree Days Concept for Current and Future Weather Projections

Citation for published version:
Mehmood, S, Amber, KP, Usman, M & Friedrich, D 2023, 'Integrating Latent Load into the Cooling Degree Days Concept for Current and Future Weather Projections', *Buildings*, vol. 14, no. 1, 106. https://doi.org/10.3390/buildings14010106

Digital Object Identifier (DOI):
10.3390/buildings14010106

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Publisher's PDF, also known as Version of record

Published In:
Buildings

buildings

MDPI

Article

Integrating Latent Load into the Cooling Degree Days Concept for Current and Future Weather Projections

Sajid Mehmood [1,2,*], Khuram Pervez Amber [3], Muhammad Usman [4] and Daniel Friedrich [1]

[1] School of Engineering, Institute for Energy Systems, The University of Edinburgh, Colin Maclaurin Road, Edinburgh EH9 3DW, UK; d.friedrich@ed.ac.uk
[2] Department of Mechanical, Mechatronics and Manufacturing Engineering (New Campus), University of Engineering & Technology, Lahore 54000, Pakistan
[3] Department of Mechanical Engineering, Mirpur University of Science and Technology (MUST), Mirpur AJK 10250, Pakistan; khuram.pervez@must.edu.pk
[4] Mechanical Engineering Department, University of Engineering and Technology, Taxila 47050, Pakistan; usman.muhammad@uettaxila.edu.pk
* Correspondence: s.mehmood@ed.ac.uk

Abstract: Rising temperatures, increase in population, and dense urban morphology have resulted in increased cooling energy demands. The conventional degree-days method to calculate cooling energy demand considers only the sensible heat load of air and neglects the latent component. This study aims to estimate the cooling degree days based on the heat index (by considering both the sensible and latent loads) for the current and future years (2050 and 2080). Further, the ventilation load index for each of these cities has been established to unlock the impact of ventilation on the building's total energy consumption for current and future years. The results show that heat index-based degree days have a stronger relationship with the buildings' cooling energy consumption and, therefore, can predict the cooling energy demand of buildings with 20% higher accuracy than conventional temperature-based degree days. Analysis shows that cooling degree-days and frequency of temperature above the comfort range continue to increase in Pakistan, highlighting increased degree-days in the range from 11.0 to 41.6% by 2050 and from 28.4 to 126.5% by 2080. Prompt actions are essential to enhance the resilience of Pakistan's national grid to meet these future cooling energy demands.

Keywords: cooling degree days; buildings; climate change; heat index; ventilation load index

check for updates

Citation: Mehmood, S.; Amber, K.P.; Usman, M.; Friedrich, D. Integrating Latent Load into the Cooling Degree Days Concept for Current and Future Weather Projections. *Buildings* **2024**, *14*, 106. https://doi.org/10.3390/buildings14010106

Academic Editor: Chi-Ming Lai

Received: 25 October 2023
Revised: 27 December 2023
Accepted: 28 December 2023
Published: 31 December 2023

1. Introduction

Greenhouse gas (GHG) emissions are the primary factor that causes global warming. The built environment is the largest energy-consuming sector globally, accounting for 35% of world energy and contributing to 38% of global energy-related emissions [1]. The built environment uses energy for space cooling, heating, lighting, hot water, and running other electrical devices. The residential sector is the most energy-intensive and leading sub-sector inside the built environment. This sector constitutes 22% of the world's primary energy consumption and emits 17% of CO_2 emissions [1]. Climate change is causing increased frequency and intensity of heat waves and extreme heat exposure. Extreme heat poses a significant risk to public health and can severely affect human health and mortality rates. Increasing heat can cause various health problems, including dehydration, heat stroke, and other heat-related illnesses, and can also exacerbate pre-existing health conditions such as respiratory issues.

Several factors like increased population density, urbanisation, transport emissions, and rising outdoor temperatures, have led to a substantial surge in the energy requirements of the building sector when it comes to providing indoor thermal comfort [2,3]. Notably, the energy demand for space cooling has surged threefold between 1990 and 2016 and continues to grow faster than other energy end uses within buildings [4]. In this context, it is paramount to establish a reliable framework for forecasting energy consumption related to space cooling. Such forecasts are crucial for shaping effective policies to meet a country's present and future energy demands.

The effect of climate change on a building's thermal energy needs is different in different parts of the world. A robust and versatile climate indicator for better estimating current and future energy needs for cooling could help devise the future strategy to meet energy needs and effective energy codes for the building sector in response to changing climate. One of the most common methods of estimating and analysing buildings' thermal energy demands is the cooling and heating degree days (CDDs and HDDs) method. Annual degree days (DDs) are calculated by integrating the differences in temperatures (i.e., ΔT between outdoor dry bulb temperature and a base temperature) for the whole year [5]. According to the American Society of Heating Ventilation and Air-Conditioning Engineers (ASHRAE), the base temperature, also known as balance point temperature, refers to a value of outdoor dry bulb temperature at which human comfort is achieved without operating cooling or heating systems. In other words, the base temperature is a fundamental notation that explains the relationship between climate, occupancy, building construction design, and the energy flow paths in a building [6]. Table 1 summarises published studies where researchers used conventional dry bulb temperature (DBT) based DDs method to calculate CDDs/HDDs for different countries. Nevertheless, the calculation of conventional DDs relying solely on the dry bulb temperature overlooks the latent component of outdoor air, focusing solely on its sensible load. In numerous regions, the latent load constitutes a substantial portion of the overall load. Using the conventional DDs calculation method for such sites could lead to an inaccurate estimation of cooling energy demands. A more robust analysis of building energy consumption could be gained by integrating both components of thermal load, i.e., sensible and latent loads. As highlighted by Scot et al. [7], humidity emerges as a significant factor influencing total building energy use. Similarly, in a study conducted by Yang et al. [8], the ambient temperature and humidity data were utilized as input for the building energy simulations to evaluate the impacts of urban local climate on the cooling and heating energy demands of a typical residential building in China.

Therefore, to calculate a building's cooling energy demands with better accuracy, considering both sensible and latent loads, DDs have been computed based on the Heat Index (HI). This index includes both DBT and relative humidity of outdoor air and, thus, incorporates both the sensible and latent components [9]. In other words, it is a measure when relative humidity is factored in with the actual air dry-bulb temperature. DDs calculation based on HI instead of only DBT could result in better estimation and forecasting of cooling energy consumption for different regions.

Table 1. Summary of temperature-based degree day published studies.

Author	**Country of Study/No. of Cities**	**Data Period**	**Reference**
Al-Hadharami (2013)	Saudi Arabia/38	1970 to 2006 (37 years)	[10]
Altan (2009)	Turkey/79	1985 to 2005 (21 years)	[11]
Berger and Worlitschek (2019)	Switzerland	1980 to 2100	[12]
Bhatnagar et al. (2018)	India/60	2018	[6]
Delphine et al. (2020)	Belgium/11	1976 to 2004 (28 years)	[13]
Elizbarashvili et al. (2018)	USA/01	1961to 1990 (29 years)	[14]

Table 1. *Cont.*

Author	Country of Study/No. of Cities	Data Period	Reference
Indraganti and Boussaa (2017)	Saudi Arabia/05	2005 to 2014 (9 years)	[15]
Islam et al.(2020)	Bangladesh/27	1980 to 2017 (37 years)	[16]
Lee et al. (2014)	South Korea/35	2001 to 2010 (10 years)	[17]
Mehrabi et al. (2011)	Iran/30	Data range not mentioned	[18]
Morakinyo et al. (2019)	Hong Kong/41	1970 to 2015 (45 years)	[19]
Orhan et al. (2001)	Turkey/78	1981 to 1998 (17 years)	[20]
Rehman et al. (2011)	Saudi Arabia	1970 to 2006 (37 years)	[21]
Rosa et al. (2015)	Italy	1978 to 2013 (35 years)	[22]
Suárez and Díaz (2019)	Dominican Republic/65	1998 to 2015 (18 years)	[23]
Verbai et al. (2014)	Hungary/25	1961 to 2010 (50 years)	[24]
Viorel and Zamfir (1999)	Romania/29	1947 to 75 (28 years)	[25]

Ventilation load is the introduction of fresh outdoor air into the building zones to provide a clean, healthy, and odour-free environment. Recently, standards have recommended higher ventilation rates for improving indoor air quality inside buildings to meet occupants' metabolic needs and dilute and remove indoor pollutants. It is estimated that ventilation load accounts for 30% of space conditioning loads [26,27]. Some codes define minimum ventilation rates in different building zones based on l/s per m^2 of floor area or l/s per person. Still, there is no maximum limit for ventilation loads. Unnecessary high ventilation rates could be a burden on building cooling needs. There is always a conflict between maximizing ventilation rates to enhance indoor air quality and minimizing ventilation rates to reduce energy related to ventilation loads. So, for the rationale of ventilation, designers need to understand the energy required to treat ventilation loads considering local weather conditions.

The effect of ventilation on total energy consumption differs in different climates due to variations in local weather conditions. The applicability of the conventional DDs method for a large-scale building with central air conditioning and ventilation system is questionable as it does not consider the ventilation load. In such built environments, outdoor air (usually at higher temperatures) is mixed with the return air, which changes the room air's sensible and latent load components. The ventilation load index (VLI) could be an appropriate solution for such studies. VLI is the thermal load (kWh) generated by one litre per second of fresh air brought to the building zone conditions for one year [28]. VLI considers sensible and latent components of the ventilation air. The VLI can be used to compare ventilation loads in different geographic locations. Availability of data related to a sensible and latent component of VLI for other regions and their impact on the total energy consumption could help better estimate cooling energy consumption and selection of air conditioning equipment to handle ventilation loads. Further, it could help develop effective policies and building codes for better thermal comfort inside building zones and minimize cooling loads. The knowledge of cooling degree days and ventilation load index for future years is helpful for policymakers to enhance the resilience of the national grid to meet these demands.

For this study, Pakistan is considered a case study as it is blessed with a unique range of altitudes from sea level to the second-highest mountains in the world. This variation in altitude gives a variety of climatic regions with huge temperature and absolute humidity ratio differences in different regions. Northern areas at higher elevations are considered cold regions, whereas its central parts, i.e., Punjab and Sindh, are extremely hot. Humidity near the southern coastal areas is higher; these regions are considered warm and humid. With the increasing urbanisation and rising global temperature, Pakistan is one of the countries suffering from severe heat waves, resulting in the loss of lives. The building sector in Pakistan is the highest energy-consuming sector, with a share of 55% of the country's total electricity consumption [29,30]. The government is facing a severe energy shortage. Especially during summer, the gap between supply and demand becomes wider, resulting in unscheduled load shedding of electricity. The increased number of air conditioners is already responsible for increased load shedding during the summer months, and there are limited available data regarding the future cooling energy demands in Pakistan. Having a good knowledge of cooling degree days and the energy required for ventilation in different regions of Pakistan could help forecast future cooling energy demands, which would indirectly help policymakers in developing effective policies and regulations. At present, no study shows the future cooling energy needs and the impact of climate on ventilation loads in different parts of the country.

The blend of the existing literature underscores a prevalent trend where a substantial portion of research on Heating Degree Days (HDDs) and Cooling Degree Days (CDDs) has mainly focused on singular weather variables, i.e., ambient temperature. Recognizing the pivotal role of humidity in the comprehensive assessment of heating and cooling load demands within building environments, this study proposes a new Degree Days (DD) calculation methodology. This innovative approach incorporates both sensible and latent loads, offering an enhanced framework for accurately estimating the cooling energy requirements across diverse regions of Pakistan. By integrating these dual components, our methodology aims to provide a more nuanced and comprehensive understanding of the dynamic factors influencing energy demand in building thermal management.

This study aims:

- To calculate and compare DDs for 39 cities of Pakistan based on DBT and HI;
- To develop a DDs map of Pakistan based on the HI;
- To establish a relationship between cooling thermal area energy density needs and DDs;
- To calculate thermal area energy density needs for annual space cooling for a residential building in distinctive climates of Pakistan;
- To investigate the impact of climate change on thermal energy needs for cooling;
- To investigate the impact of climate change on ventilation load for different cities of Pakistan.

2. Methodology

The conceptual framework employed in this research is shown in Figure 1. Overall work can be divided into the following main parts: (1) creation of future weather files; (2) calculation of degree days based on temperature and heat index; (3) calculation of ventilation load index; (4) spatial maps with ArcGI; (5) numerical model of a building to calculate cooling energy demand; and (6) comparison of temperature and heat index based degree days with numerical model results. In Section 2.1, the methodology for generating future weather files is explained. Section 2.2 discusses the methods employed for calculating degree days based on dry bulb temperature and heat index, while Section 2.3 discusses the methods for calculating the ventilation load index. The last two subsections (Sections 2.4 and 2.5) detail the validated numerical model developed within the TRNSYS simulation framework.

2.1. Climate Data

Emission scenarios defined by the Intergovernmental Panel on Climate Change (IPCC) are essential inputs for Global Climate Models (GCMs), the most complex models for forecasting climate change. GCMs mathematically simulate the general circulation of a planetary atmosphere, representing interactions between the atmosphere, ocean, and land surface, ultimately predicting Earth's climate changes over time. While GCM models predict meteorological parameters, they typically provide monthly data with a resolution spanning 100–200 km at various altitudes. However, this level of detail is insufficient for building simulation tools, as many building systems require hourly simulation data. The morphing technique developed by Belcher et al. is used to downscale monthly data to hourly resolution [31]. The University of Southampton's Energy and Climate Change group developed the Climate Change World Weather File Generator (CCWorldWeatherGen) tool based on this technique. This tool transforms original EnergyPlus weather files into 'climate change' weather files and has been widely used by researchers [31–34]. More details about this tool can be found in [35,36]. In this study, we collected current typical weather files for 39 cities in Pakistan from 'Climate.OneBuilding.Org' [37], an online repository of free climatic data for energy modelling, and future weather files (2050 and 2080) were created CCWorldWeatherGen v1.8.

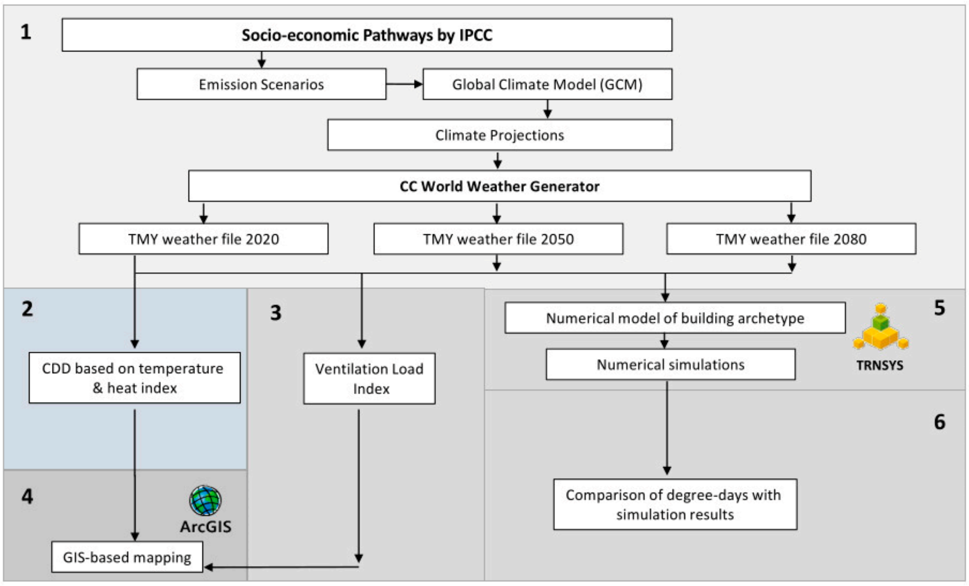


Figure 1. Study conceptual framework.

2.2. Cooling Degree Days Calculations

This section is divided into two subsections. The first section (Section 2.2.1) discusses the temperature-based cooling degree days methodology. The second section (Section 2.2.2) defines the heat methods index-based cooling degree days. The details are provided in the following sections.

2.2.1. Temperature-Based Cooling Degree Days

In this section, the temperature-based cooling degree day method is discussed. Based on hourly weather data, Equation (1) was used to calculate annual cooling degree days.

$$\mathrm{CDD_{yearly,temp}} = \frac{\sum_{i=1}^{8760} (\mathrm{T_{a,i}} - \mathrm{T_b})^{+}}{24} \quad (1)$$

where T_a shows hourly ambient temperature, i indicates the respective hour of the year, and + indicates that only positive differences between ambient and base temperatures are considered. T_b is called base temperature, which is defined as the outdoor air temperature at which there is no need to switch on heating or cooling equipment. Base temperature varies by building archetypes, internal gains, building fabric, and outdoor design conditions. Ahmed [38] developed a mathematical relation for calculating base temperature as a function of building indoor design temperature, internal gains, solar heat gains, and overall building heat transfer coefficient. Krese et al. [39] described the energy signature and performance line method for calculating base temperature. These methods are based on each building's daily or monthly electrical energy consumption data, resulting in base temperatures tailored to the location and specific building. This large data requirement and the building-specific base temperature make these methods unsuitable for comparative studies. Since this study aims to calculate cooling degree days for 39 cities in Pakistan, we figured degree days with the base temperature recommended by ASHRAE, i.e., 18.3 °C [40]. This base temperature is used in many studies [20,41] and enables the effective comparison between different cities. The calculation of degree days considering the different base temperatures in this study is also discussed.

2.2.2. Heat Index-Based Cooling Degree Days

This section presents the methodology for calculating heat index and degree days based on heat index calculation. The heat index (HI) is the air temperature that incorporates the effect of both temperature and relative humidity [42]. The algorithm used to calculate the heat index is shown in Figure 2. HI_B is the computation of the heat index obtained by multiple regression analyses carried out by Rothfusz [42]. Mathematically, it can be written with Equation (2).

$$HI_B = -42.379 + 2.040 \times T + 10.143 \times RH - 0.225 \times T \times RH - 0.007 \times T^2 - 0.055 \times RH^2 + 0.001 \times T^2 \times RH^2 + 0.0008 \times T \times RH^2 - 0.000001999 \times T^2 \times RH^2 \quad (2)$$

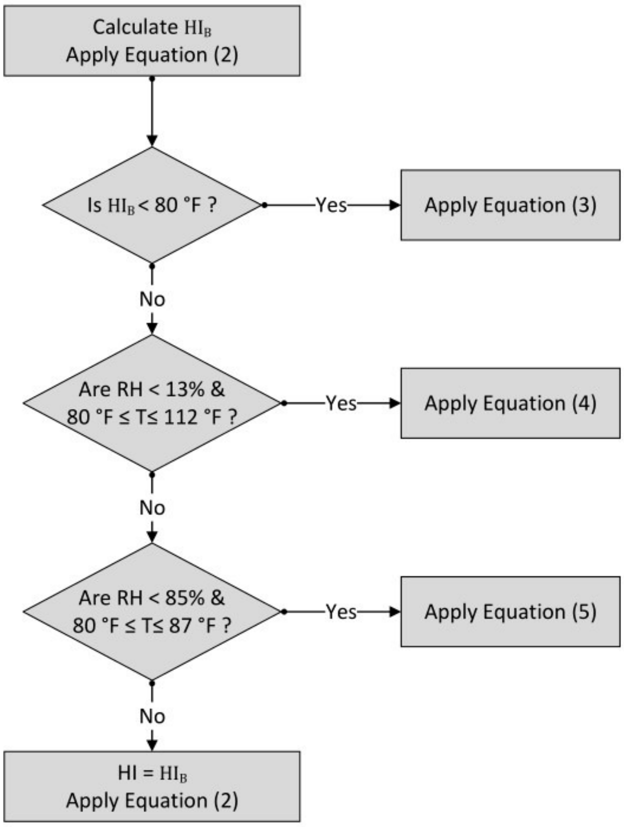


Figure 2. The algorithm for calculating heat index: T is the ambient temperature in °F; RH is the relative humidity of outdoor air; and ABS and SQRT are the absolute value and square root functions, respectively.

The Rothfusz regression is inappropriate when temperature and humidity warrant a heat index below 80 °F. In those cases, a simple formula (Equation (3)) is applied to calculate values consistent with Steadman's results [43].

$$HI = 0.5 \times \{T + 61 + [(T - 68) \times 1.2] + (RH \times 0.094)\} \quad (3)$$

Adjustments occur if the heat index value reaches or exceeds 80 °F. If the relative humidity (RH) falls below 13% and the temperature falls within the 80 to 112 °F range, Equation (4) is employed to calculate the necessary adjustment.

$$\mathrm{I} = \mathrm{HI_B} - \left(\frac{13 - \mathrm{RH}}{4}\right) \times \left(\frac{\sqrt{(17 - \mathrm{ABS}(\mathrm{T} - 95)}}{\sqrt{17}}\right) \tag{4}$$

Yet, if the relative humidity (RH) surpasses 85% and the temperature falls within the range of 80 to 87 °F, Equation (5) is applied for the necessary adjustment.

$$\mathrm{HI} = \mathrm{HI_B} + \left(\frac{\mathrm{RH} - 85}{10}\right) \times \left(\frac{87 - \mathrm{T}}{5}\right) \tag{5}$$

Once the heat index temperature is calculated from the algorithm given in Figure 2, it is converted into a celcius (°C) scale. Then, using this value, cooling degree days have been calculated using Equation (6).

$$\mathrm{CDD_{yearly,HI}} = \frac{\sum_{i=1}^{8760}(\mathrm{HI_i} - \mathrm{HI_{base}})^{+}}{24} \tag{6}$$

2.3. Ventilation Load Index (VLI)

One of the major sources of thermal load for an air conditioner is ventilation. Ventilation is the replacement or exchange of room air with fresh outdoor air. This adds both the sensible and latent loads to the space. The climatic conditions differ in different regions of Pakistan concerning the elevation from sea level. Therefore, ventilation load differs for other cities, making sensible and latent loads a function of local ambient conditions (dry bulb temperature and humidity ratio). To estimate the impact of different ventilation rates on a building's energy consumption, ventilation-associated sensible and latent loads in different climates should be known to the HVAC designer. In this study, the ventilation load index (VLI) has been calculated for 39 cities in Pakistan, which is defined as the energy required to bring the unit flow rate of outside air (litre per second) to building design conditions over a whole year [28]. It consists of a sensible cooling component (kWh per litre per year) and a latent component (latent kWh per litre per second per year).

The sensible load for cooling the air from the outside temperature ($\mathrm{t_o}$) to the desired indoor temperature ($\mathrm{t_i}$) is calculated as

$$\mathrm{Q_{sens}} = \mathrm{C_p V}\rho(\mathrm{t_o} - \mathrm{t_i}) \tag{7}$$

Latent load for the dehumidification of the air from the outdoor humidity ratio ($\mathrm{W_o}$) to the desired indoor $\mathrm{W_i}$;

$$\mathrm{Q_{lat}} = \rho(\mathrm{W_o} - \mathrm{W_i})\mathrm{h_{fg}} \tag{8}$$

where $\mathrm{c_p}$ is the specific heat capacity of air (1 kJ/kgK), ρ is the density of air (1.2 kg/m^3), V is the volumetric flow of outdoor ventilation air (litre per second), $\mathrm{h_{fg}}$ is the latent heat of vaporization (2500 kJ/kg). In this study, we have calculated the sensible and latent load per unit of volumetric airflow to compare the sensible and latent load in different cities of Pakistan. The results of $\mathrm{Q_{sens}}$ and $\mathrm{Q_{lat}}$ are in kWh. The ventilation load index gives quick information about comparing sensible and latent loads in other geographic locations from the ambient air. This parameter provides valuable information to the design engineer to deal with ventilation loads in calculating total space cooling loads. VLI is a suitable index for comparing climates and informing the designer about appropriate technologies when looking at design loads.

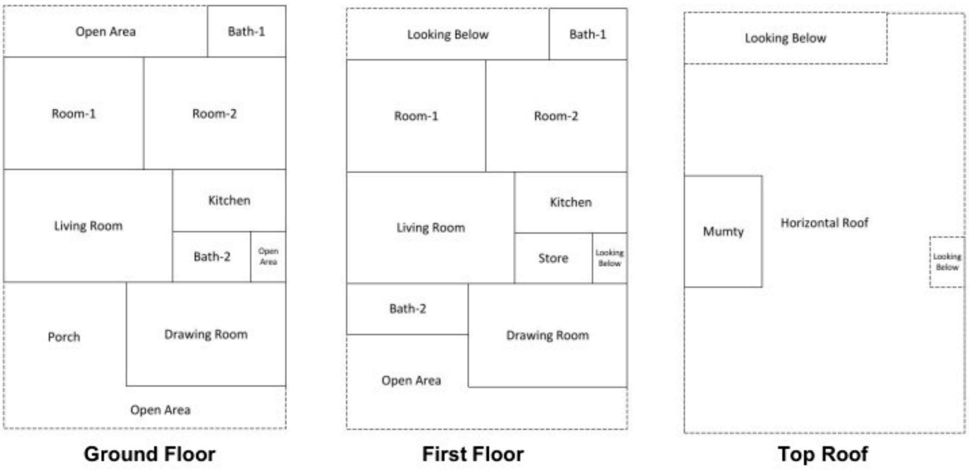
2.4. Numerical Model for Calculation of Cooling Energy Demand

In this study, we developed a numerical model within the simulation software TRNSYS (Trnsys System Simulation) v18, which is popular among researchers involved in building energy modelling [44]. TRNSYS offers a range of pre-built models known as 'TYPES' designed for various applications, including single-zone and multi-zone building simulations, ventilation components, and diverse cooling and heating systems. This extensive library of pre-configured models within TRNSYS made it an ideal choice for our research.

Building Model

Figure 3a shows the selected building's archetype. The chosen building, representing a standard multifamily two-storey design in Pakistan, comprises three bedrooms, a living room, a kitchen, and two bathrooms on each floor. The flow diagram for simulation methodology is shown in Figure 3b, where SketchUp was used to create a 3D model. To incorporate the building characteristics, it was imported into TRNBuild. Finally, TRNSYS simulation studio implements different weather files to calculate the thermal energy demand for space cooling. The TRNSYS model is shown in Figure 4. The details about the internal gains, their variability, control logic, and building design conditions can be found in the author's previous studies [45].

a, Geometry plan of the selected building archetype



b, Flow diagram for simulation methodology

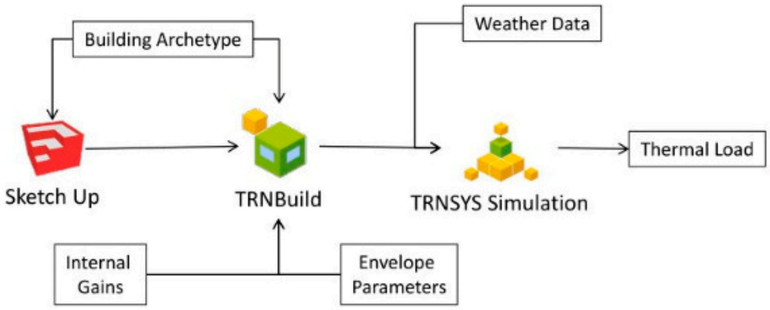


Figure 3. (**a**) Geometry plan of selected building archetype; (**b**) Flow diagram for simulation methodology.

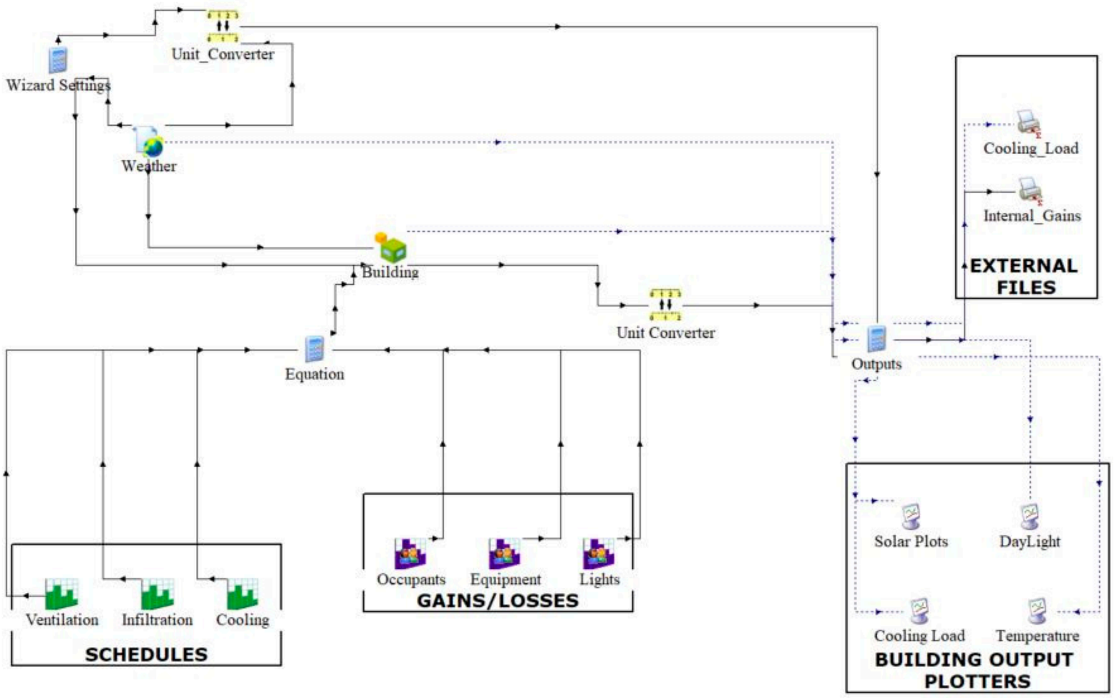


Figure 4. Building model simulated in TRNSYS.

2.5. Validation of Numerical Model

This study validated the numerical model according to ASHRAE guidelines [46]. This involved employing three key metrics: normalized mean bias error (NMBE); coefficient of variation in the root mean square error (CV-RMSE); and coefficient of determination (R^2). NMBE is a normalization of the MBE index used to scale and produce comparable results; CV-RMSE quantifies the error variability between measured and simulated values, and R^2 assesses how closely our predictions align with the actual data's trend. ASHRAE recommends that an effective numerical model exhibit an NMBE below 5% and a CV-RMSE below 15% compared to monthly calibration data. Additionally, R^2 should surpass 0.75. This study validated the numerical model using actual energy data. We adjusted specific parameters until our numerical model matched the actual measurements, as illustrated in Figure 5.

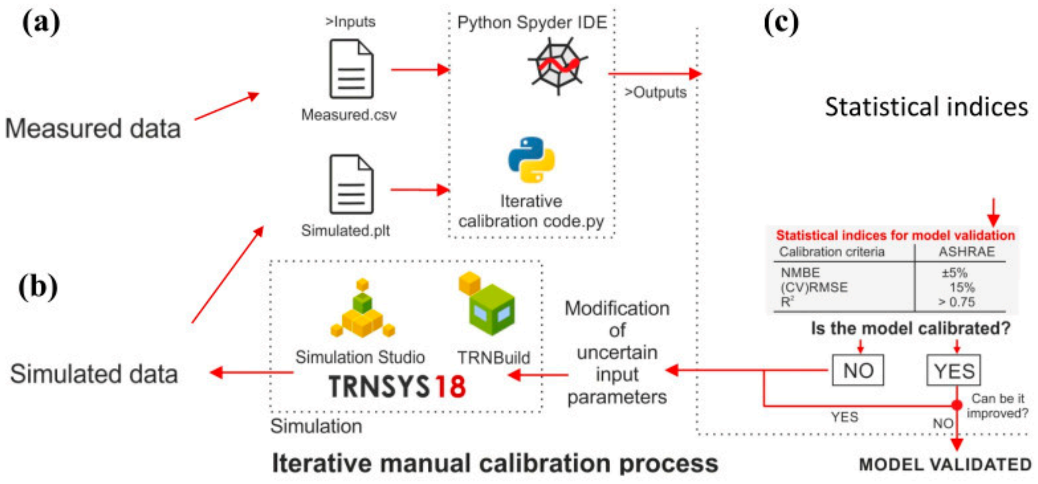


Figure 5. Iterative manual calibration workflow for model validation. (**a**) measured data. (**b**) simulated data. (**c**) After each simulation interaction, the results of the Python script provide the statistical indices to verify the model's accuracy and validate the model.

The comparison of actual and simulated data revealed an NMBE of 3.3%, a CV-RMSE of 9.1%, and an R^2 of 0.9, satisfying the criteria outlined in the ASHRAE standard [46].

3. Results and Discussions

This section shows the results and discussion of degree days with temperature and heat index approach and comparison with a validated numerical model. In addition, it shows the variation in latent heat index due to climate change. Overall, the results are divided into the following sections. First, the degree days based on temperature and heat index are discussed (Section 3.1). Second, the ventilation load index for different cities of Pakistan for current and future years is discussed (Section 3.2). Finally, the results of temperature and heat-index-based degree days are compared and discussed with a validated numerical model.

3.1. Cooling Degree Days Based on Temperature and Heat Index

This section discusses the results related to annual cooling degree days based on temperature (conventional approach) and heat index (proposed method) for different cities of Pakistan using Equations (1) and (3). Figure 6 shows the CDDs for the year 2020 based on outdoor dry bulb temperature and heat index as a function of elevation in the corresponding cities considering a base temperature of 18.3 °C (ASHRAE recommended base temperature). Interestingly, cooling degree days' values based on heat index are higher than CDDs' values based on temperature. This could be attributed to CDDs based on heat index incorporating the effect of relative humidity (latent load). In contrast, CDDs based on simple dry bulb temperature do not consider the relative humidity factor (latent load). Figure 6 also depicts that CDDs based on heat index have a stronger linear relationship with the elevation (R^2 = 0.9) than DBT-based CDDs with an R^2 value of 0.8. The results demonstrate a negative linear relationship between the city's elevation and its cooling degree days. The cities at lower elevations have higher CDDs, and cities at higher elevations have lower CDDs. The overall analysis of 39 cities of Pakistan has revealed that the southern and eastern parts of Pakistan are energy-intensive regions in terms of cooling energy. In contrast, the northern areas at a higher elevation have a lower cooling energy demand. For example, Sibi and Sukkur, located at 134 m and 58 m, have 5.5 and 5.1 times higher temperature-based CDDs than Parachinar at a higher elevation (1726 m). Similarly, based on heat index-based CDDs, Sibi and Sukkur have 7.2 and 6.6 times more CDDs than Parachinar, which is at a higher elevation. It has been observed that Murree has the lowest and Sibi has the highest CDDs among the 39 cities.

Figure 7 shows the filled colour map of cooling degree days of 39 cities of Pakistan based on the heat index for the years 2020, 2050, and 2080. The coloured sections of Figure 7 represent the region containing the selected 39 cities that cover Pakistan's main urban areas. The white areas consist of regions where no cities have been considered in this study, as their data were unavailable. It was found that most of the cities located in Khyber Pakhtunkhwa (KPK) province are located in the north of Pakistan, and some cities in Balochistan province, like Zhob, Kalat, Khuzdar, and Barkhan, have lower values of cooling degree days. The importance of heat index-based cooling degree days in the Punjab province varies from 3000 to 3700 degrees. The cooling degree days in the central Sindh province of Pakistan, i.e., Jacobabad and Sukkur, were 4885 and 4932, respectively. The highest value of cooling degree days from the 39 cities was found in Sibi, located in the Balochistan province of Pakistan. The cooling degree days for this city were calculated to be 5386. The data analysis has revealed that for the cities between zero to 1500 m elevation, the number of CDDs will increase by 16% and 47% in 2050 and 2080, respectively, compared to 2020. For the cities having elevation more significant than 1500 m, the number of CDDs will increase by 25% and 71% in 2050 and 2080, respectively, compared to 2020. This means global warming will have more impact on the future cooling energy demands for the cities located at higher elevations than those with lower elevations. This could be attributed to the fact that the cities at higher elevations have higher humidity ratios in the summer, resulting in higher latent load. These findings must be integrated into Pakistan’s future energy policies.

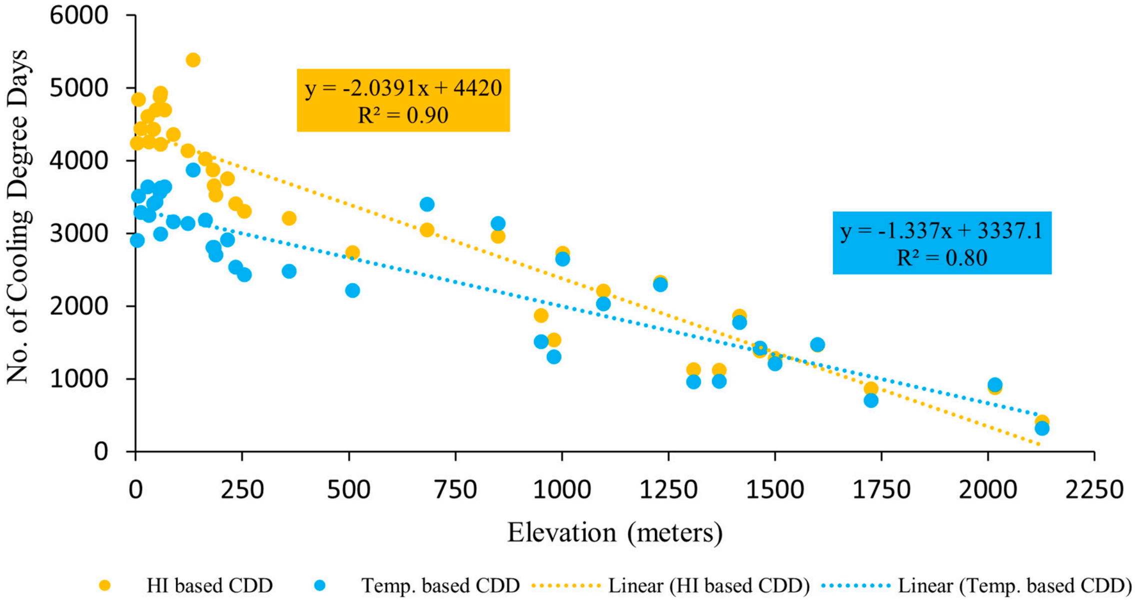
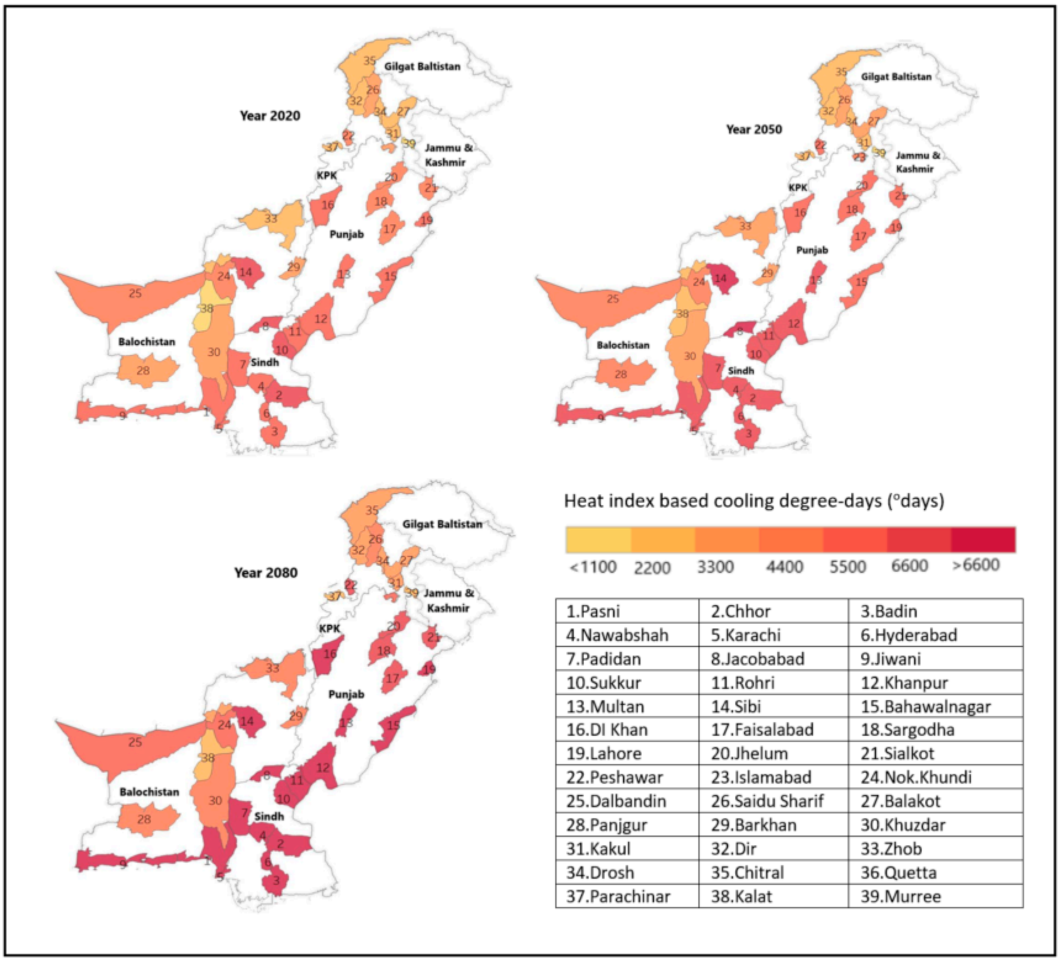


Figure 6. Cooling Degree Days (2020) as a function of elevation in the corresponding cities.



1.Pasni	2.Chhor	3.Badin
4.Nawabshah	5.Karachi	6.Hyderabad
7.Padidan	8.Jacobabad	9.Jiwani
10.Sukkur	11.Rohri	12.Khanpur
13.Multan	14.Sibi	15.Bahawalnagar
16.DI Khan	17.Faisalabad	18.Sargodha
19.Lahore	20.Jhelum	21.Sialkot
22.Peshawar	23.Islamabad	24.Nok.Khundi
25.Dalbandin	26.Saidu Sharif	27.Balakot
28.Panjgur	29.Barkhan	30.Khuzdar
31.Kakul	32.Dir	33.Zhob
34.Drosh	35.Chitral	36.Quetta
37.Parachinar	38.Kalat	39.Murree

Figure 7. Heat index-based cooling degree days for different cities of Pakistan for 2020, 2050, and 2080.

Figure 8 shows the number of CDDs at various base temperatures for the capital cities (i.e., Lahore, Karachi, Peshawar, and Quetta) of four provinces for the years 2020, 2050, and 2080 for a base temperature of 10, 14, 18.3 and 22 °C. It is found that the number of CDDs decreases with the increase in the base temperature. The result shows that due to climate change, the number of CDDs in 2050 and 2080 for Lahore is 18% and 52% higher compared to 2020, whereas the increase in CDDs for Karachi, Quetta, and Peshawar is also in a similar range for the years 2050 and 2080. This means that, on average, cooling degree days of these four major cities will increase by 17% and 47% in the years 2050 and 2080, respectively.

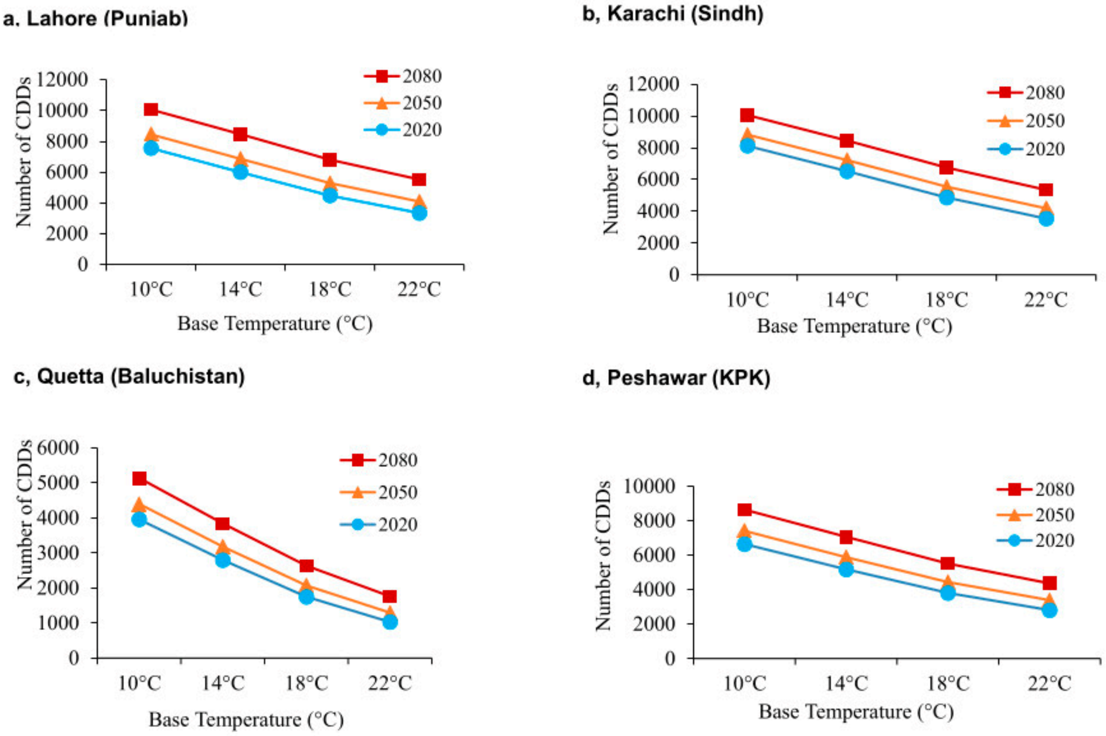
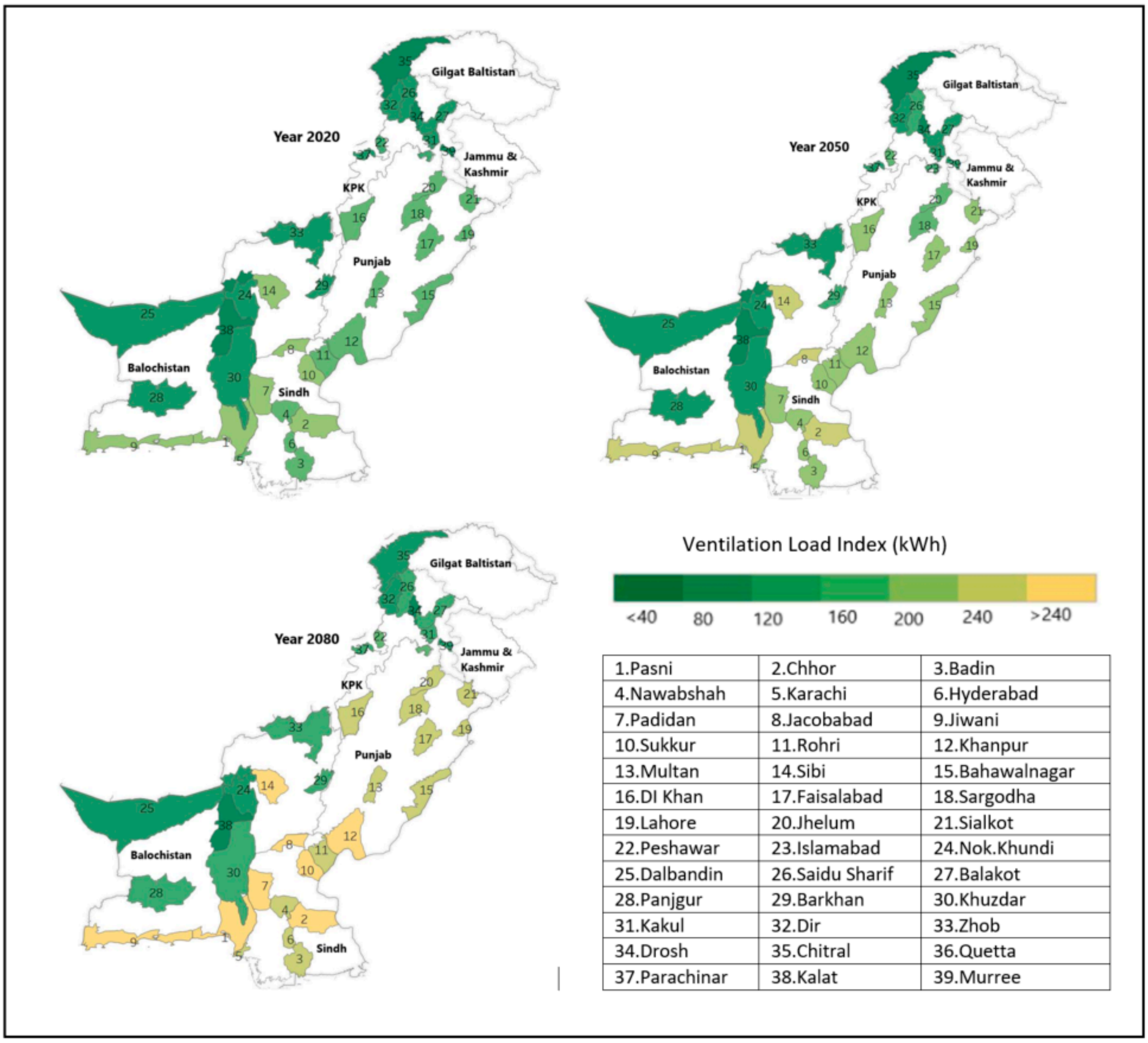


Figure 8. Heat index-based degree days at different base temperatures for 2020, 2050, and 2080.

3.2. *Ventilation Load Index for Different Cities of Pakistan*

In this section, the impact of ventilation, including the share of the sensible and latent component of load in buildings on energy consumption for different cities of Pakistan, is presented and discussed. The ventilation load index calculation results are shown in Figure 9 in a filled colour map for other cities of Pakistan for the years 2020, 2050, and 2080. White spaces in the map show that weather stations or weather data for these locations are unavailable for the current study.

The results show that the maximum ventilation load index value in 39 investigated cities was found in Sibi (176 kWh) in Balochistan for 2020. This ventilation load index value will increase to 209 kWh (+19%) and 261 kWh (+33%) by 2050 and 2080, respectively. If we compare this with central Punjab cities, for example, with Lahore, then VLI for Sibi is 1.3 times higher than Lahore for the year 2020, which means for the same amount of ventilation in Lahore and Sibi, 1.3 times more energy is required to bring outside air to zone conditions in Sibi than Lahore. Overall, it is found that the VLI has a negative correlation with the elevation in corresponding cities, which means that the VLI decreases with an increase in elevation. It can be noticed that the areas that lie at higher elevations (towards the north) have lower VLI, and it increases towards the coastal regions (southern side). On the other hand, a minimum ventilation load index was found in Kalat (8.89 kWh) in 2020. Over the years, this will also increase to 12.6 (+42%) and 20.2 kWh (+127%) for the years 2050 and 2080, respectively. The overall average ventilation load index of all investigated cities is found to be 102 kWh, and this will increase to 126 kWh and 166 kWh by 2050 and 2080, respectively.



1.Pasni	2.Chhor	3.Badin
4.Nawabshah	5.Karachi	6.Hyderabad
7.Padidan	8.Jacobabad	9.Jiwani
10.Sukkur	11.Rohri	12.Khanpur
13.Multan	14.Sibi	15.Bahawalnagar
16.DI Khan	17.Faisalabad	18.Sargodha
19.Lahore	20.Jhelum	21.Sialkot
22.Peshawar	23.Islamabad	24.Nok.Khundi
25.Dalbandin	26.Saidu Sharif	27.Balakot
28.Panjgur	29.Barkhan	30.Khuzdar
31.Kakul	32.Dir	33.Zhob
34.Drosh	35.Chitral	36.Quetta
37.Parachinar	38.Kalat	39.Murree

Figure 9. Ventilation load index for different cities of Pakistan for the years 2020, 2050 and 2080.

The variation in the average ventilation load index, including sensible and latent components in different elevation bands, is shown in Figure 10. It can be noticed that the sensible and latent parts of VLI have a negative correlation with the elevation in corresponding cities, and values of both sensible and latent components have increased over the years. The areas situated at higher elevations have lower sensible loads. The sensible element of VLI varies from 1 to 62.5 kWh per litre per second per year for 2020. The minimum sensible component of VLI is found in Murree because the temperature in this city lies within the comfort zone most of the year, and only a cooling load is required due to dehumidification. On the other hand, the maximum value of sensible load for 2020 is found in Sibi (62.5 kWh). The analysis of the latent component of the ventilation load shows that the minimum value is found in Nok. Khundi (0.02 kWh), while the maximum value was registered for Pasni (145 kWh) in 2020. The sensible and latent component values of the ventilation load index for 2020, 2050, and 2080. It is valuable information for the designers of HVAC system design ventilation systems for air-conditioned buildings in different regions.

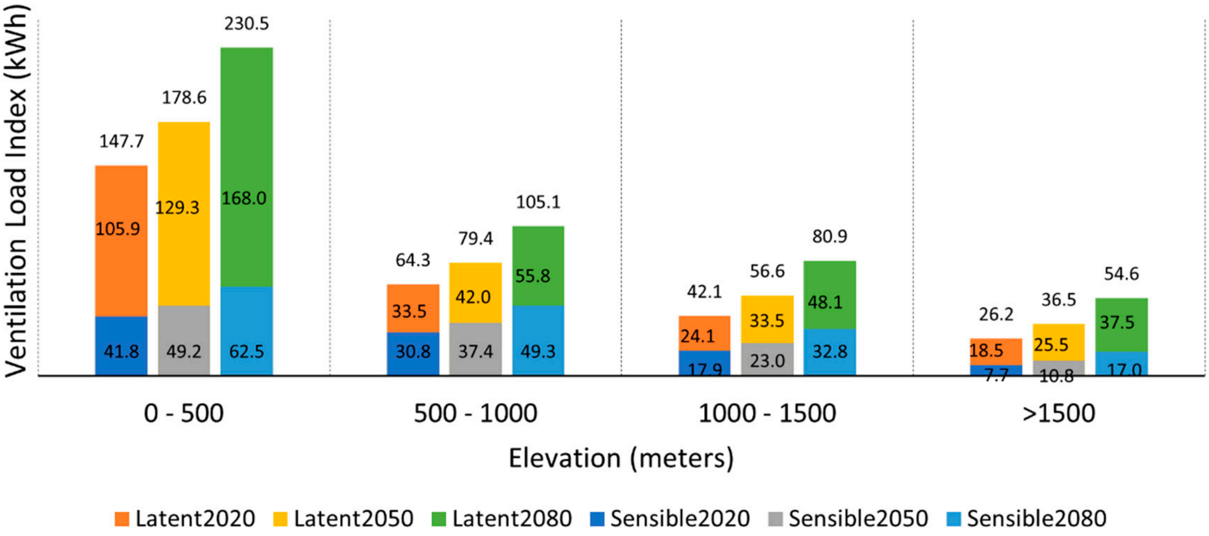


Figure 10. Ventilation load index at different elevation bands for 2020, 2050, and 2080.

The data analysis has revealed that for the cities located between zero to 500 m elevation, the VLI, including sensible and latent components for such cities, will increase by 21% and 56% in the years 2050 and 2080, respectively, compared to 2020 (147.7 kWh). Similarly, the average VLI for cities in the elevation range of 500–1000 m showed higher VLI for 2050 (+23%) and 2080 (+63%), respectively, compared to 2020. It is interesting to note that the rate of increase in VLI for cities at an elevation level more fabulous than 1000 m is higher than for cities at an elevation level of less than 1000 m. For example, the rate of increase in VLI for cities located at 1000–1500 m is 34% and 92% by 2050 and 2080, respectively. Similarly, for cities with elevation levels greater than 1500 m, VLI will increase by 39 and 108% in 2050 and 2080, respectively. This means global warming will impact the cities in higher elevations more than those in lower elevations. These findings must be integrated into Pakistan's future energy policies.

3.3. Thermal Area Energy Density for Space Cooling for a Typical Residential Building

This section presents the results of thermal energy demand for space cooling for residential buildings in different climates, assuming the same fabric and internal gains using TRNSYS, as described in Section 2.4. The simulation results represent the annual thermal energy demand for space cooling in kWh/m^2 for 39 cities in Pakistan (Figure 11). It is interesting to note that a high cooling demand exists in cities at lower elevations. With an increase in elevation, the demand for seasonal cooling energy is reduced significantly. For example, let us compare the average annual cooling energy needs for a building in cities with an elevation below 150 m (144 kWh/m^2) with cities above 1525 m (14 kWh/m^2). Results show that 10.6 times more energy is required in the towns at a lower elevation to achieve the same indoor thermal comfort. If we compare the space energy cooling requirements for cities of central Punjab (lie in elevation from 150 to 300 m) with Sindh Province (cities below 150 m elevation), then, on average, cities at an elevation of below 150m need 1.2 times more energy than sites at an elevation from 150 to 300 m.

Figure 12 shows the correlation between degree days and the annual thermal cooling demand calculated from a numerical model. The graph shows a strong positive linear relation between CDDs and space thermal cooling energy needs. To evaluate the goodness of fit of temperature- and HI-based degree days with TRNSYS simulation results of annual thermal load, we used the coefficient of determination (R^2) method. This is a widely used statistical measure to determine the goodness of fit. Our results show that the correlation coefficient of determination (R^2) value for CDDs based on heat index (0.96) is better than CDDs based on temperature (0.83) with annual space thermal cooling needs calculated from TRNSYS.

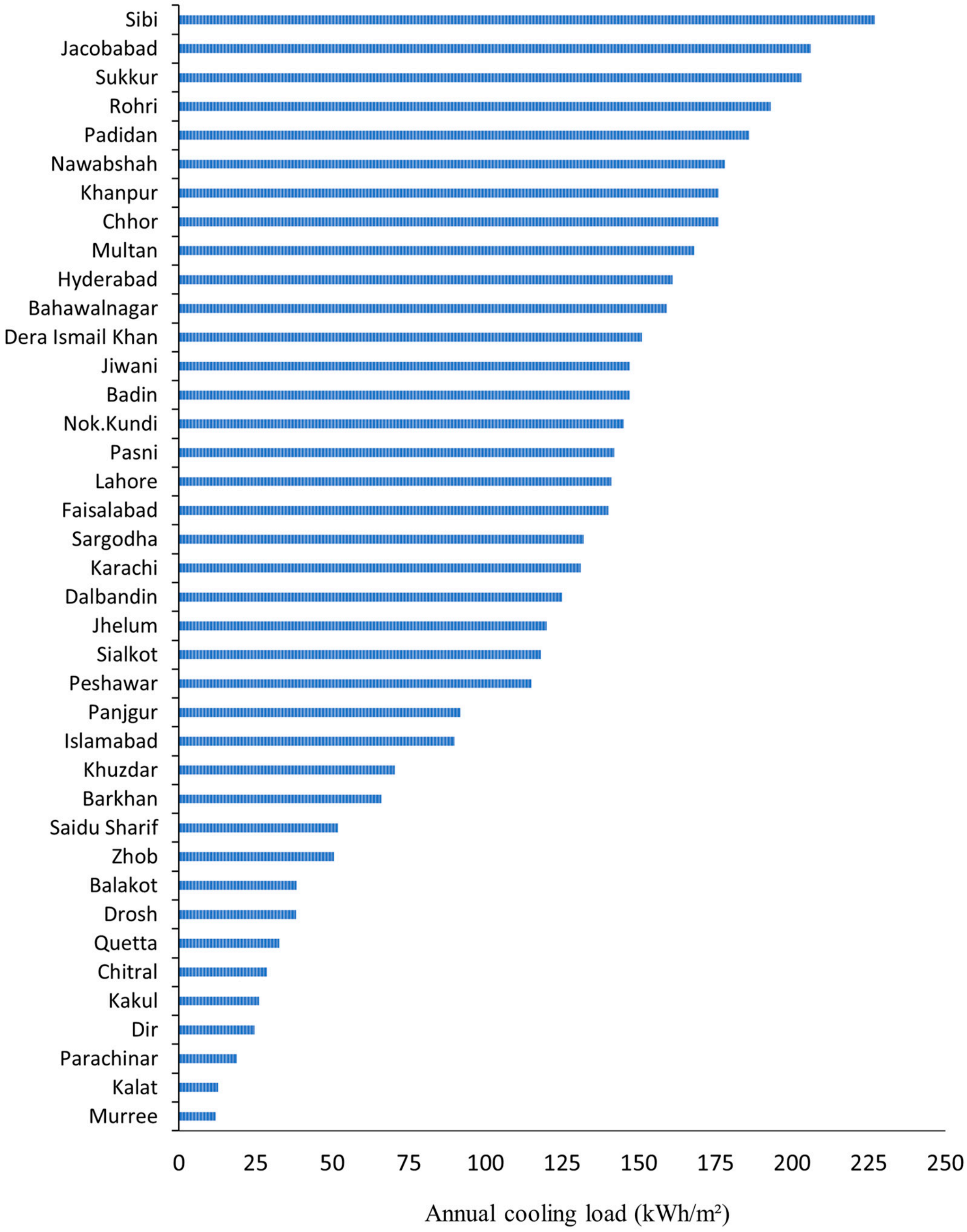


Figure 11. Thermal energy demand for cooling in different cities in Pakistan (2020).

The outcomes of our study reveal that the coefficient of determination (R^2) values associated with CDDs predicated on heat index and temperature exhibit notable distinctions in their predictive efficacy for annual space thermal cooling needs, as computed through TRNSYS. Specifically, the R^2 value for CDDs derived from the heat index is 0.96. This robust correlation coefficient signifies an exceptionally strong association, indicative of the heightened accuracy achieved when utilizing the heat index as a predictor. This model accounts for 96% of the observed variance in annual space thermal cooling needs.

Conversely, the R^2 value for CDDs based on temperature is recorded at 0.83. Although still indicative of a robust correlation, this value falls short of the precision achieved with the heat index. The temperature-derived model explains 83% of the observed variance in annual space thermal cooling needs. Overall, the findings underscore that, within the parameters of our study, employing the heat index as a predictive variable yields a superior model for estimating annual space thermal cooling needs when compared to relying solely on temperature. The discernibly higher R^2 value associated with the heat index attests to its enhanced reliability as a predictive indicator in our analytical framework.

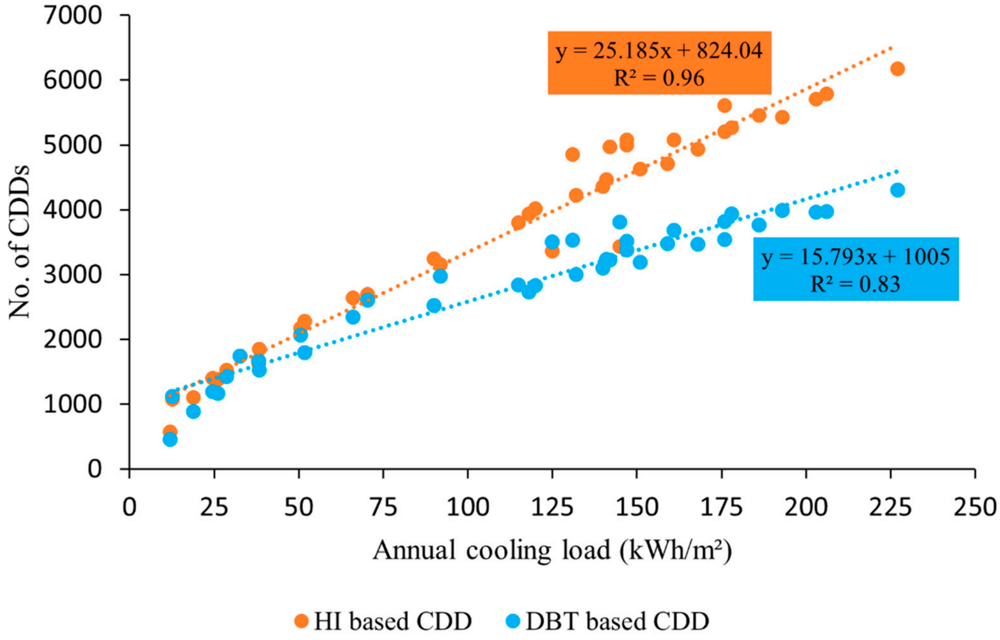


Figure 12. Correlation between thermal cooling energy demand and number of cooling degree days.

4. Conclusions

Cooling degree days are a common and widely used method for forecasting buildings' cooling energy demand. A critical shortcoming of the conventional temperature-based degree day method lies in neglecting the latent load. In this study, an improved method based on heat index is proposed, and the results are shown with spatial maps considering Pakistan as a case study. Furthermore, the variation in the ventilation load index and annual area thermal energy density for space cooling requirements of different cities of Pakistan are calculated. Overall, the following conclusions can be drawn:

(1) Degree day values based on heat index are higher than degree days based on dry bulb temperature. This is because CDDs based on heat index incorporate the effect of relative humidity (latent load). It is also shown that cooling degree days have a linear negative relation with the elevation in the corresponding cities of Pakistan. The cities at lower elevations have higher cooling energy demands and vice versa. The results demonstrate that HI-based CDDs display a stronger relationship with the annual cooling demand calculated from the numerical model with an R^2 value of 0.96 compared to $R^2 = 0.80$ for the conventionally calculated CDDs. Based on this analysis, HI-based CDDs are recommended;

(2) For cities of Pakistan between zero and 1500 m elevation, the number of CDDs will increase by 16% and 47% in 2050 and 2080, respectively, compared to 2020. For cities with elevations more than 1500 m, the number of CDDs for such cities will increase by 25% and 71% in 2050 and 2080, respectively, compared to 2020. This means global warming will impact the future cooling energy demands for the cities located at higher elevations than those in lower elevations of Pakistan. This could be attributed to the fact that the cities at higher elevations have higher humidity ratios in the summer, resulting in higher latent load. These findings must be integrated into Pakistan's future energy policies;

(3) Selecting an optimal base temperature is vital for higher energy savings. With the increasing base temperature, the number of CDDs decreases. Specifically, elevating the base temperature from 18 to 22 degrees Celsius results in a substantial decrease in CDDs: 1138 for Lahore; 1322 for Karachi; 718 for Quetta; and 1001 for Peshawar;

(4) For the same design conditions, the energy required to treat the ventilation air differs in different parts of the country. The maximum energy required for ventilation is registered in Sibi (176 kWh), while the lowest is found in Kalat (8.9 kWh) in 2020. The sensible and latent component of VLI also varies. It is also shown that the ventilation load index has a negative linear relationship with the elevation in corresponding cities. However, the analysis indicates that in future years, i.e., 2050 and 2080, the VLI for the cities located at higher elevations will increase more than for those at lower elevations;

(5) Thermal energy needs for space cooling are linearly related to degree days. Central Punjab and most of Pakistan's Sindh and Baluchistan provinces exhibit higher demand for space cooling energy, whereas regions situated at higher elevations experience comparatively lower space cooling requirements. However, the analysis shows that in future years, 2050 and 2080, the demand for cooling for the cities located at higher elevations will increase more than for those at lower elevations;

(6) In light of these findings, the utilization of CDDs based on the heat index is recommended, as they exhibit a stronger correlation with the annual cooling demand when compared to conventionally calculated CDDs. This underscores the enhanced predictive capability of CDDs incorporating relative humidity, offering a more accurate assessment of cooling needs in the context of the studied cities in Pakistan.

In a nutshell, this study underscores the limitations of the conventional degree days method in forecasting the energy demands of buildings, particularly due to its oversight of the latent component of thermal load. The findings advocate adopting a Heat Index (HI) based Cooling Degree Days (CDD) approach, deeming it more contemporary and robust. Incorporating the latent load, represented by the HI, enhances the accuracy of predictions regarding future energy demands. In the context of an energy-constrained nation like Pakistan, the implications of this study are far-reaching. The insights gleaned are valuable for building designers, investors, owners, and policymakers, offering a foundation for the development of informed energy consumption policies within the building sector. The recommendation to shift towards a more advanced and inclusive HI-based CDD methodology holds the potential to contribute significantly to energy efficiency efforts and sustainable building practices. Moreover, this study provides pertinent information regarding the ventilation load index, which proves instrumental for HVAC design engineers. Armed with this knowledge, engineers can tailor ventilation equipment designs more effectively, aligning them with the specific thermal demands of the environment. This not only enhances the overall efficiency of HVAC systems but also contributes to the optimization of energy utilization in buildings, a crucial consideration in regions facing energy scarcity. Ultimately, this study's multifaceted implications extend from advancing forecasting methodologies to informing practical design considerations, thereby contributing to a more sustainable and energy-conscious built environment.

Author Contributions: S.M., conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, software, visualization, writing—original draft; K.P.A., conceptualization, methodology, formal analysis, writing—review and editing; M.U., methodology, software, validation, writing—review and editing; D.F., conceptualization, funding acquisition, investigation, project administration, resources, supervision, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research has received financial support from the Higher Education Commission of Pakistan, the University of Engineering and Technology, Lahore, New Campus, Pakistan, and the UK ESRC Cool infrastructure project (ES/T008091/1).

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature and Abbreviations

c_p	specific heat capacity of air
DBT	dry bulb temperature
DD	degree day
GCM	general circulation model
GHG	greenhouse gas emissions
HDD	heating degree day
h_{fg}	latent heat of vaporisation
HI	heat index
IPCC	Intergovernmental panel on climate change
RCM	regional climate model
RH	relative humidity
T	temperature
VLI	ventilation load index

References

1. Global Status Report for Buildings and Construction 2019—Analysis—IEA. Available online: https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019 (accessed on 4 April 2022).
2. Miranda, N.; Lizana, J.; Sparrow, S.; Zachau-walker, M.; Watson, P.; Wallom, D.; Khosla, R.; Mcculloch, M. Change in Cooling Degree Days with Global Mean Temperature Increasing from 1.5° to 2.0 °C. *Nat. Sustain.* **2023**, *6*, 1326–1330. [CrossRef]
3. Remizov, A.; Memon, S.A.; Kim, J.R. Climate Zoning for Buildings: From Basic to Advanced Methods—A Review of the Scientific Literature. *Buildings* **2023**, *13*, 694. [CrossRef]
4. IEA. The Future of Cooling: Opportunities for Energy-Efficient Air Conditioning. Available online: https://www.iea.org/reports/the-future-of-cooling (accessed on 25 March 2023).
5. Spinoni, J.; Vogt, J.V.; Barbosa, P.; Dosio, A.; McCormick, N.; Bigano, A.; Füssel, H.-M.M. Changes of Heating and Cooling Degree-Days in Europe from 1981 to 2100. *Int. J. Climatol.* **2018**, *38*, e191–e208. [CrossRef]
6. Bhatnagar, M.; Mathur, J.; Garg, V. Determining Base Temperature for Heating and Cooling Degree-Days for India. *J. Build. Eng.* **2018**, *18*, 270–280. [CrossRef]
7. Scott, M.J.; Wrench, L.E.; Hadley, D.L. Effects of Climate Change on Commercial Building Energy Demand. *Energy Sour.* **2007**, *16*, 317–332. [CrossRef]
8. Yang, X.; Yao, L.; Peng, L.L.H. Impacts of Urban Air Temperature and Humidity on Building Cooling and Heating Energy Demand in 15 Cities of Eastern China. *Energy* **2024**, *288*, 129887. [CrossRef]
9. Zune, M.; Rodrigues, L.; Gillott, M. The Vulnerability of Homes to Overheating in Myanmar Today and in the Future: A Heat Index Analysis of Measured and Simulated Data. *Energy Build.* **2020**, *223*, 110201. [CrossRef]
10. Al-Hadhrami, L.M. Comprehensive Review of Cooling and Heating Degree Days Characteristics over Kingdom of Saudi Arabia. *Renew. Sustain. Energy Rev.* **2013**, *27*, 305–314. [CrossRef]
11. Dombayci, Ö.A. Degree-Days Maps of Turkey for Various Base Temperatures. *Energy* **2009**, *34*, 1807–1812. [CrossRef]
12. Berger, M.; Worlitschek, J. The Link between Climate and Thermal Energy Demand on National Level: A Case Study on Switzerland. *Energy Build.* **2019**, *202*, 109372. [CrossRef]
13. Ramon, D.; Allacker, K.; De Troyer, F.; Wouters, H.; van Lipzig, N.P.M.M. Future Heating and Cooling Degree Days for Belgium under a High-End Climate Change Scenario. *Energy Build.* **2020**, *216*, 109935. [CrossRef]
14. Elizbarashvili, M.; Chartolani, G.; Khardziani, T. Variations and Trends of Heating and Cooling Degree-Days in Georgia for 1961–1990 Year Period. *Ann. Agrar. Sci.* **2018**, *16*, 152–159. [CrossRef]
15. Indraganti, M.; Boussaa, D. A Method to Estimate the Heating and Cooling Degree-Days for Different Climatic Zones of Saudi Arabia. *Build. Serv. Eng. Res. Technol.* **2017**, *38*, 327–350. [CrossRef]
16. Islam, A.R.M.T.; Ahmed, I.; Rahman, M.S. *Trends in Cooling and Heating Degree-Days Overtimes in Bangladesh? An Investigation of the Possible Causes of Changes*; Springer: Dordrecht, The Netherlands, 2020; Volume 101, ISBN 0123456789.
17. Lee, K.; Baek, H.J.; Cho, C.H. The Estimation of Base Temperature for Heating and Cooling Degree-Days for South Korea. *J. Appl. Meteorol. Climatol.* **2014**, *53*, 300–309. [CrossRef]
18. Mehrabi, M.; Kaabi-Nejadian, A.; Khalaji Asadi, M. Providing a Heating Degree Days (HDDs) Atlas across Iran Entire Zones. In Proceedings of the World Renewable Energy Congress, Linköping, Sweden, 8–13 May 2011; Volume 57, pp. 1039–1045. [CrossRef]
19. Morakinyo, T.E.; Ren, C.; Shi, Y.; Lau, K.K.L.; Tong, H.W.; Choy, C.W.; Ng, E. Estimates of the Impact of Extreme Heat Events on Cooling Energy Demand in Hong Kong. *Renew. Energy* **2019**, *142*, 73–84. [CrossRef]
20. Büyükalaca, O.; Bulut, H.; Yılmaz, T. Analysis of Variable-Base Heating and Cooling Degree-Days for Turkey. *Appl. Energy* **2001**, *69*, 269–283. [CrossRef]
21. Rehman, S.; Al-Hadhrami, L.M.; Khan, S. Annual and Seasonal Trends of Cooling, Heating, and Industrial Degree-Days in Coastal Regions of Saudi Arabia. *Theor. Appl. Climatol.* **2011**, *104*, 479–488. [CrossRef]

22. De Rosa, M.; Bianco, V.; Scarpa, F.; Tagliafico, L.A. Historical Trends and Current State of Heating and Cooling Degree Days in Italy. *Energy Convers. Manag.* **2015**, *90*, 323–335. [CrossRef]
23. Peña Suárez, J.N.; del Campo Díaz, V.J. Degree-Days in a Caribbean and Tropical Country: The Dominican Republic's Case. *Int. J. Ambient Energy* **2021**, *42*, 795–800. [CrossRef]
24. Verbai, Z.; Lázár, I.; Kalmár, F. Heating Degree Day in Hungary. *Environ. Eng. Manag. J.* **2014**, *13*, 2887–2892. [CrossRef]
25. Badescu, V.; Zamfir, E. Degree-Days, Degree-Hours and Ambient Temperature Bin Data from Monthly-Average Temperatures (Romania). *Energy Convers. Manag.* **1999**, *40*, 885–900. [CrossRef]
26. Garshasbi, S.; Haddad, S.; Paolini, R.; Santamouris, M.; Papangelis, G.; Dandou, A.; Methymaki, G.; Portalakis, P.; Tombrou, M. Urban Mitigation and Building Adaptation to Minimize the Future Cooling Energy Needs. *Sol. Energy* **2020**, *204*, 708–719. [CrossRef]
27. Liddament, M. A Guide to Energy Efficient Ventilation. *Phys. Rev. B* **1996**, *51*, 274.
28. Papakostas, K.T.; Slini, T. Effects of Climate Change on the Energy Required for the Treatment of Ventilation Fresh Air in HVAC Systems the Case of Athens and Thessaloniki. *Procedia Environ. Sci.* **2017**, *38*, 852–859. [CrossRef]
29. Amber, K.P.; Ahmad, R.; Farmanbar, M.; Bashir, M.A.; Mehmood, S.; Khan, M.S.; Saeed, M.U. Unlocking Household Electricity Consumption in Pakistan. *Buildings* **2021**, *11*, 566. [CrossRef]
30. Mehmood, S.; Maximov, S.A.; Chalmers, H.; Friedrich, D. Energetic, Economic and Environmental (3E) Assessment and Design of Solar-Powered HVAC Systems in Pakistan. *Energies* **2020**, *13*, 4333. [CrossRef]
31. Mehmood, S.; Lizana, J.; Núñez-Peiró, M.; Maximov, S.A.; Friedrich, D. Resilient Cooling Pathway for Extremely Hot Climates in Southern Asia. *Appl. Energy* **2022**, *325*, 119811. [CrossRef]
32. Ptootkaboni, M.; Ballarini, I.; Zinzi, M.; Corrado, V. A Comparative Analysis of Different Future Weather Data for Building Energy Performance Simulation. *Climate* **2021**, *9*, 37. [CrossRef]
33. Jiang, A.; Liu, X.; Czarnecki, E.; Zhang, C. Hourly Weather Data Projection Due to Climate Change for Impact Assessment on Building and Infrastructure. *Sustain. Cities Soc.* **2019**, *50*, 101688. [CrossRef]
34. Invidiata, A.; Ghisi, E. Impact of Climate Change on Heating and Cooling Energy Demand in Houses in Brazil. *Energy Build.* **2016**, *130*, 20–32. [CrossRef]
35. Jentsch, M.F.; Bahaj, A.S.B.S.; James, P.A.B.B. Climate Change Future Proofing of Buildings—Generation and Assessment of Building Simulation Weather Files. *Energy Build.* **2008**, *40*, 2148–2168. [CrossRef]
36. Jentsch, M.F.; James, P.A.B.; Bourikas, L.; Bahaj, A.B.S. Transforming Existing Weather Data for Worldwide Locations to Enable Energy and Building Performance Simulation under Future Climates. *Renew. Energy* **2013**, *55*, 514–524. [CrossRef]
37. Climate.Onebuilding.Org. Available online: https://climate.onebuilding.org/ (accessed on 7 February 2021).
38. Safwat Chapter IV Balance Point Temperature and the Evaluation of the Building's Thermal Performance. Available online: https://patents.google.com/patent/EP3101602A1/en (accessed on 18 August 2023).
39. Krese, G.; Prek, M.; Butala, V. Analysis of Building Electric Energy Consumption Data Using an Improved Cooling Degree Day Method. *Stroj. Vestn. -J. Mech. Eng.* **2012**, *58*, 107–114. [CrossRef]
40. ASHRAE. *ASHRAE Handbook–Fundamentals*; SI Edition; ASHRA: Peachtree Corners, GA, USA, 2017; ISBN 6785392187.
41. Shanmuga Priya, S.; Premalatha, M.; Rajkumar, S.R.; Thirunavukkarasu, I. Analysis of Cooling Degree Days for Tiruchirappalli—A District in India. *Int. J. Res. Rev. Appl. Sci.* **2011**, *8*, 44–56.
42. Rothfusz, L.P. The Heat Index Equation. *Fort Worth Texas Natl. Ocean. Atmos. Adm. Natl. Weather Serv. Off. Meteorol.* **1990**, 23–90.
43. Brooke Anderson, G.; Bell, M.L.; Peng, R.D. Methods to Calculate the Heat Index as an Exposure Metric in Environmental Health Research. *Environ. Health Perspect.* **2013**, *121*, 1111–1119. [CrossRef]
44. Mehmood, S.; Lizana, J.; Friedrich, D. Solar-Driven Absorption Cooling System with Latent Heat Storage for Extremely Hot Climates. *Energy Convers. Manag.* **2023**, *297*, 117737. [CrossRef]
45. Mehmood, S.; Lizana, J.; Friedrich, D. Low-Energy Resilient Cooling through Geothermal Heat Dissipation and Latent Heat Storage. *J. Energy Storage* **2023**, *72*, 108377. [CrossRef]
46. ASHRAE Guideline 14-2014. Measurement of Energy, Demand, and Water Savings. Available online: https://www.ashrae.org/technology (accessed on 3 February 2022).