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Présentée par JAOUAF Salaheddine

Titre

Contribution à l'Étude de l'inertie Thermique et des Performances Énergétiques du Bâtiment dans la Wilaya de Ain Temouchent

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Theme

Contribution to the Study of the Thermal Inertia and the Energy Performance of the Buildings in the Wilaya of Ain-Temouchent

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Abstract

This doctoral thesis investigates the critical role of passive strategies in enhancing the energy efficiency and thermal comfort of buildings in Mediterranean climates, with a focus on the province of Ain Temouchent, Algeria. The research comprises two distinct yet interrelated studies conducted in the region.

The first study delves into the energy efficiency of residential buildings, particularly focusing on the impact of insulation and glazing on energy consumption and indoor thermal comfort. Through theoretical analyses and simulation using TRNSYS 17 software, the study evaluates various insulation materials and glazing options available in the Algerian market. Findings reveal that wood fiber insulation with a 9 cm thickness demonstrates superior thermal performance, yielding a notable 26% reduction in energy costs compared to conventional insulation materials. Moreover, transitioning from single to double glazing leads to substantial reductions in heating and cooling expenses, underscoring the significance of appropriate insulation and glazing choices in achieving energy efficiency and enhancing occupants' comfort.

The second study centers on optimizing the energy performance of educational facilities, specifically primary school classrooms, through passive design strategies. By leveraging simulations validated against actual electricity consumption data, the research identifies key optimizations, including external shading devices, Window-to-Wall Ratio (WWR) adjustments, and the utilization of double-low-emissivity (Double-Low E) glazing. Noteworthy findings include the significant energy savings achieved through a Vertical Shading Angle (VSA) of 60°, a recommended WWR of 30%, and the integration of Double-Low E glazing, resulting in an impressive 44% overall reduction in energy consumption.

Collectively, these studies underscore the efficacy of passive strategies in mitigating energy demand and promoting sustainable building practices in Mediterranean climates. The findings contribute valuable insights for architects, engineers, and policymakers involved in the design and construction of energy-efficient buildings, while also advocating for the adoption of ecologically responsible practices to address the challenges of climate change and energy sustainability.

Keywords
Energy efficiency, Heat transfer, Heating Cooling loads, Passive strategies, Thermal comfort, TRNSYS 17.

Résume

Cette thèse doctorale examine le rôle crucial des stratégies passives dans l'amélioration de l'efficacité énergétique et du confort thermique des bâtiments dans les climats méditerranéens, avec un accent particulier sur la province d'Aïn Témouchent, en Algérie. La recherche se compose de deux études distinctes mais interdépendantes menées dans la région.

La première étude se penche sur l'efficacité énergétique des bâtiments résidentiels, en mettant particulièrement l'accent sur l'impact de l'isolation et du vitrage sur la consommation d'énergie et le confort thermique intérieur. À travers des analyses théoriques et des simulations réalisées à l'aide du logiciel TRNSYS 17, l'étude évalue divers matériaux d'isolation et options de vitrage disponibles sur le marché algérien. Les résultats révèlent que l'isolation en fibres de bois d'une épaisseur de 9 cm présente une performance thermique supérieure, entraînant une réduction notable de 26 % des coûts énergétiques par rapport aux matériaux d'isolation conventionnels. De plus, le passage d'un vitrage simple à un vitrage double conduit à des réductions substantielles des dépenses de chauffage et de refroidissement, soulignant ainsi l'importance des choix appropriés en matière d'isolation et de vitrage pour atteindre l'efficacité énergétique et améliorer le confort des occupants.

La deuxième étude se concentre sur l'optimisation de la performance énergétique des établissements éducatifs, en particulier les salles de classe des écoles primaires, à travers des stratégies de conception passive. En exploitant des simulations validées par des données réelles de consommation d'électricité, la recherche identifie des optimisations clés, notamment les dispositifs de protection solaire externes, les ajustements du rapport fenêtre-mur et l'utilisation de vitrage à double émissivité réduite (Double-Low E). Des résultats remarquables incluent les importantes économies d'énergie obtenues grâce à un angle de protection solaire vertical de 60°, un rapport fenêtre-mur recommandé de 30 % et l'intégration de vitrage Double-Low E, aboutissant à une impressionnante réduction globale de 44 % de la consommation énergétique.

Dans l'ensemble, ces études soulignent l'efficacité des stratégies passives dans la réduction de la demande énergétique et la promotion de pratiques de construction durables dans les climats méditerranéens. Les résultats apportent des insights précieux pour les architectes, ingénieurs et décideurs impliqués dans la conception et la construction de bâtiments économes en énergie, tout en plaidant en faveur de l'adoption de pratiques écologiquement responsables pour relever les défis du changement climatique et de la durabilité énergétique.

Mots clé
Efficacité énergétique, Transfert de chaleur, Charges de chauffage et de refroidissement, Stratégies passives, Confort thermique, TRNSYS 17.

الملخص

تتناول الأطروحة الدور الحيوي للإستراتيجيات السلبية في تعزيز كفاءة الطاقة والراحة الحرارية للمباني في مناخ البحر الأبيض المتوسط، مع تركيز الدراسة على ولاية عين تموشنت بالجزائر، حيث يتألف البحث من دراستين متميزتين ومترابطتين تم إجراؤهما في المنطقة.

تستهدف الدراسة الأولى كفاءة الطاقة في المباني السكنية، مع التركيز بشكل خاص على تأثير العزل والزجاج في استهلاك الطاقة والراحة الحرارية الداخلية. من خلال التحليلات النظرية والمحاكاة باستخدام برنامج TRNSYS 17 ، حيث قيمت الدراسة مواد العزل المختلفة وخيارات الزجاج المتاحة في السوق الجزائرية وأظهرت النتائج أن العزل بألياف الخشب بسماكة 9 سم يؤدي أداءً حراريًا متفوقًا، بما يقلل النسبة إلى 26% فيما يتعلق بتكاليف إستهلاك الطاقة مقارنة بالمواد العازلة التقليدية. علاوة على ذلك، يؤدي كذلك التحول من الزجاج الأحادي إلى الزجاج المزدوج إلى تقليل نفقات التدفئة والتبريد بشكل أكبر، مما يبرز أهمية مواد العزل وأنواع الزجاج في تحقيق كفاءة الطاقة وتعزيز راحة السكان.

في حين تتمحور الدراسة الثانية على تحسين الأداء الطاقوي للمرافق التعليمية وتحديداً الصفوف الدراسية في المدرسة الابتدائية، من خلال استراتيجيات التصميم السلبي للإستفادة من المحاكاة الموثقة ببيانات فعلية لاستهلاك الطاقة، حيث يحدد البحث التحسينات الرئيسية، بما في ذلك أجهزة التظليل الخارجية وتعديل مساحة النافذة بالنسبة إلى مساحة الجدار واستخدام الزجاج ذو الإشعاع المنخفض المزدوج، بالإضافة إلى إجراء بعض التعديلات في غلاف المبنى، حيث توصلنا إلى مجموعة من النتائج تتعلق أساسا بتوفير الكفاءات الطاقوية الكبيرة والتقليل منها بنسبة 44% والمحققة من خلال دمج زاوية التظليل الرأسي بزاوية 60 درجة وكذلك حجم النافذة بنسبة 30% مقارنة بالجدار، بالإضافة إلى دمج الزجاج ذو الإشعاع المنخفض المزدوج.

بشكل عام، تؤكد هذه الدراسات فعالية الاستراتيجيات السلبية في تقليل استهلاك الطاقة وتعزيز الممارسات البنائية المستدامة في مناخ البحر الأبيض المتوسط، حيث تسهم النتائج في تنوير المعماريين و المهندسين عند تصميم و بناء المباني ذات الكفاءة من الناحيتين الطاقوية و البيئية، مما يساهم في مواجهة تحديات التغير المناخي والاستدامة الطاقوية.

كلمات مفتاحية

كفاءة الطاقة، نقل الحرارة، أحمال التدفئة والتبريد، استراتيجيات سلبية، الراحة الحرارية، TRNSYS 17.

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I will be eternally grateful to you all

Dedication

In closing, I dedicate this work to the honorable martyrs in Gaza, may their souls find solace in the embrace of the Almighty, and may they find eternal peace in the vast heavens above. My prayers extend to the steadfast freedom fighters in the cherished land of Palestine, may they be granted victory in their noble struggle for justice and liberation.

With sincere thanks,

JAOUAF Salaheddine

Contribution

This section delineates the significant contributions made throughout the course of my doctoral journey conducted at the Smart Structure Laboratory (SSL), located at Ain-Temouchent Belhadj Bouchaib, Algeria. It serves to document the scholarly endeavors and accomplishments attained during the research tenure.

Journal Publications

- Jaouaf, S., Bensaad, B., & Habib, M. (2024). Passive strategies for energy-efficient educational facilities: Insights from a mediterranean primary school. Energy Reports, 11, 3653-3683. https://doi.org/10.1016/j.egyr.2024.03.040 [**Class A**]
- Jaouaf, S., Bensaad, B., & Dorbane, A. (2024). Energy efficiency of a house in Mediterranean region: insulation and glazing impact. The Journal of Engineering and Exact Sciences, 10(1), 17038-17038. https://doi.org/10.18540/jcecvl10iss1pp17038 [**Class B**]
- Jaouaf, S. E., & Bensaad, B. (2023). Studying the peak loads of simple single-zone by TRNSYS. Journal of Applied Energies, 2(1), 27-35.

Conference Publications

- Jaouaf, S. E., Bensaad, B., & Taleb, S. (2022, November). Evaluation of Thermal and Energy Performance of a Primary School in the Mediterranean Environment. In *International Conference on Advanced Renewable Energy Systems* (pp. 319-329). Singapore: Springer Nature Singapore. [**Class B**]

Conference Presentations

Presentations at International Conferences

- Jaouaf, S., & Bensaad, B. (2022). Evaluation of thermal and energy performance of a primary school in the Mediterranean environment. '*1st International Conference on Advanced Renewable Energy Systems ICARES'22, 18–20 Dec, Tipaza, Algeria*'.
- Jaouaf, S., & Bensaad, B. (2022). Enhance the thermal and energy efficiency of a primary school in the Wilaya of Ain-Temouchent by concentrating on solar gains. '*1st International Conference on Renewable Materials and Energies ICRME'22, 26-27 Oct, Ouargla, Algeria*'.

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- Jaouaf, S., & Bensaad, B. (2023). Examining the impact of glazing design on energy consumption in primary school building. *'The study day on Composite Materials and Energy Technologies CMET'23, 14 Dec, Ain-Temouchent, Algeria'.*
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- Jaouaf, S., & Bensaad, B. (2019). Contribution to the study of the thermal inertia and the energy performance of the buildings in the Wilaya of Ain Temouchent. '*World Day for Safety and Health at Work*, 28 Apr, Ain-Temouchent, Algeria'.

Not Related to the Thesis

Presentations at International Conferences

- Taleb, S., Hadji, B., M'hamdi, F., & Jaouaf, S. (2021). Performance de structure à connection evolutive. '*2nd International Conference on Civil Engineering ICCE'21, 24-25 Nov, Laghouat, Algeria'.*
- M'hamdi, F., Derriche, Z., Taleb, S., & Jaouaf, S. (2021). Contribution of databases in soil. '*2nd International Conference on Civil Engineering ICCE'21, 24-25 Nov, Laghouat, Algeria'.*

Presentations at National Conferences

- M'hamdi, F., Hani, M., Jaouaf, S., & Derriche, Z. (2023). Investigation sur l'importance des bases de données dans le domaine de la recherche sur les sols. '*National Seminar on Geotechnics for Infrastructure Development NSGID'23, 12 Dec, Relizane, Algeria'.*

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Nomenclature and Abbreviations

Nomenclature

$\dot{Q}_{Surf,i}$	The convective gain from surfaces.	[kJ/hr]
$\dot{Q}_{\inf,i}$	The infiltration gains (airflow from outside only)	[kJ/hr]
$\dot{Q}_{vent,i}$	The ventilation gains (airflow from a user-defined source, like an HVAC system)	[kJ/hr]
$\dot{Q}_{g,c,i}$	The internal convective gains (by people, equipment, illumination, radiators, etc.)	[kJ/hr]
$\dot{Q}_{cp\lg,i}$	The gains due to (connective) airflow from air node i or boundary condition	[kJ/hr]
$\dot{Q}_{solair,i}$	The fraction of solar radiation entering an air node through external windows is immediately transferred as a convective gain to the internal air	[kJ/hr]
$\dot{Q}_{ISHCCI,i}$	The absorbed solar radiation on all internal shading devices of the zone and directly transferred as a convective gain to the internal air	[kJ/hr]
$\dot{m}_{\inf,i}$	Mass flow rate of infiltration air	[kg/hr]
$\dot{m}_{v,k,i}$	Mass flow rate of ventilation air of ventilation type k	[kg/hr]
c_p	Specific heat of the air	[kJ/kg K]
$T_{v,k}$	Temperature of ventilation air of ventilation type k	[°C]
T_a	Ambient air temperature	[°C]
$\dot{Q}_{solair,i}$	Solar radiation enters the air node through external windows which are immediately transferred as a radiative gain to the air node i	[kJ/hr]
$f_{solair,i}$	Is the solar to air fraction to the air node i	[-]
$I_{trans,dif,i}$	Is the diffuse solar radiation transmitted through all external windows of the air node i	[kJ/m^2]
$I_{trans,dir,i}$	Is the direct solar radiation transmitted through all external windows of the air node i	[kJ/m^2]
Δt	The simulation time-step	[hr]
$T_{i,\tau-\Delta t}$	The air node temperature at the beginning of the time-step	[°C]
P_i	Power output for air node I (negative for heating, positive for cooling).	[W]
$P_{\max,i}$	Absolute value of the maximum power for air node i	[W]
$T_{set,i}$	Set temperatures for heating or cooling in air node i	[°C]
$T_{req,i}$	The average air node temperature over the time-step	[°C]
U_{center}	U-value of the glazing is calculated as a shunt circuit of the center of glass value	[kJ/ hr m^2 K]
U_{edge}	U-value of the glazing edge	[kJ/ hr m^2 K]

$f_{\text{int},sh}$	Non transparent fraction of internal shading related to the total glass area	[-]
$refl_{sh,i}$	Solar reflection of internal shading facing the glass	[kJ/m^2]
$refl_{sh,o}$	Solar reflection of internal shading facing the room	[kJ/m^2]
$refl_{win,i}$	Solar reflection of glass surface facing the internal shading device	[kJ/m^2]
$trans_{win}$	Solar transmittance of all window panes	[-]
$\dot{m}_{cplg,s}$	Mass flow rate of air entering air node i across walls or windows	[kg/hr]
$T_{s,i}$	Inside surface temperature	[°C]
$T_{s,o}$	Outside surface temperature	[°C]
$S_{s,i}$	Radiation heat flux absorbed at the inside surface (solar and radiative gains)	[kJ/m^2]
$S_{s,o}$	Radiation heat flux absorbed at the outside surface (solar gains)	[kJ/m^2]
$A_{s,i}$	The inside surface area	[m^2]
$\dot{q}_{s,i}$	Conduction heat flux from the wall at the inside surface	[kJ/hr]
$\dot{q}_{s,o}$	Into the wall at the outside surface	[kJ/hr]
$\dot{q}_{comb.s,i}$	the combined convective and radiative heat flux	[kJ/hr]

Abbreviations

IEA	International Energy Agency
UNEP	United Nations Environment Program
IPCC	Intergovernmental Panel on Climate Change
BIM	Building Information Modelling
IEQ	Indoor Environmental Quality
IAQ	Indoor Air Quality
VOCs	Volatile Organic Compounds
LEED	Leadership in Energy and Environmental Design
ASHRAE	The American Society of Heating, Refrigerating, and Air-Conditioning Engineers
HVAC	Heating, Ventilation, and Air Conditioning systems
PET	Potential Evapotranspiration
TMI	Thornthwaite Moisture Index
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
CLC	Cellular Lightweight Concrete
CFFT	Complex Finite Fourier Transform
WFR	Window to Floor Ratio
DF	Daylight Factor
VSA	Vertical Shading Angle
AEC	Annual Energy Consumption

1 Introduction and Problematic

1.1 Overview

1.1.1 Worldwide Energy Consumption in the Building Sector. Specifically, in Algeria

The building sector stands at the forefront of global energy consumption, constituting a significant share of the world's energy demand. Fueled by rapid urbanization, population growth, and the integration of energy-intensive technologies, the need for electricity, heating, and cooling in residential, commercial, and industrial buildings continues to surge, shaping overarching energy consumption patterns [1]. Urbanization emerges as a pivotal factor, transforming cities into epicenters of energy demand, while technological advancements, such as smart buildings and energy-intensive technologies, further contribute to the global thirst for energy in the building sector [2].

In the unique context of Algeria, situated at the crossroads of Africa and the Mediterranean, the interplay of traditional and modern architecture, coupled with a burgeoning population, defines the nation's distinctive energy needs. Urbanization in cities like Algiers, Oran, and Constantine amplifies energy demand, while rural areas contribute to a diverse energy landscape. Algeria grapples with challenges such as energy access disparities, ageing infrastructure, and the imperative for sustainable development. Negotiating these challenges, the building sector in Algeria becomes a focal point for addressing disparities and leveraging opportunities, aligning with the nation's commitment to innovation and energy efficiency, as outlined in the National Energy Strategy [3] and guided by insights into energy consumption patterns in urban and rural areas [4]. This intricate interplay between global trends and localized dynamics positions Algeria as a noteworthy case study, offering valuable lessons for shaping policies and practices that foster a resilient, sustainable, and energy-efficient built environment.

The buildings and construction industry accounted for the largest share of global final energy use 37% and energy-related CO_2 emissions 40% in 2022 [5,6].

Figure 1-1 illustrates the substantial role of the building sector in global energy consumption patterns for the year 2022.

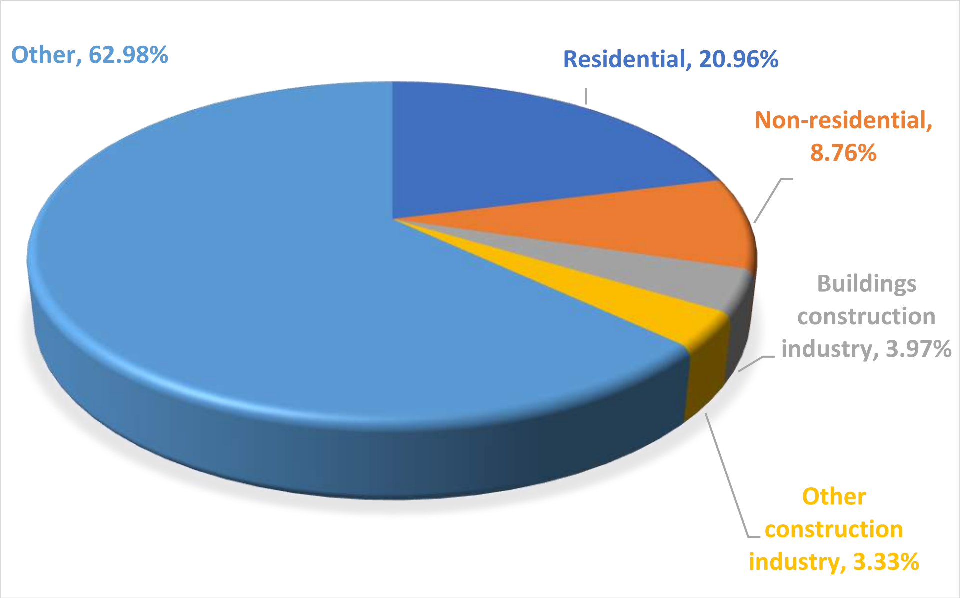


Figure 1-1 Final energy consumption of buildings relative to other sectors, 2022 [5,6]

1.1.2 Environmental Impact of Worldwide Energy Consumption in the Building Sector: A Closer Look at Algeria

The global building sector, a formidable consumer of energy, assumes a pivotal role in the production of carbon dioxide emissions, a key catalyst for climate change. In Algeria, this impact is palpable as fossil fuel combustion for electricity, heating, and construction processes underscores the nation's energy landscape [7]. Algeria's historical reliance on fossil fuels permeates its energy mix, leaving a lasting imprint on CO2 emissions within the building sector. Despite strides in diversification, carbon-intensive energy production endures, necessitating a comprehensive analysis of emissions tied to electricity generation, heating, and construction practices. The environmental ramifications extend beyond energy consumption to the materials integral to construction, with the extraction, manufacturing, and transportation of these materials contributing significantly to CO2 emissions [8]. In the context of rapid urbanization and infrastructure development, Algeria grapples with a heightened environmental impact. Concurrently, the specter of global warming looms large, transcending geographical boundaries and presenting unique challenges in Algeria. The nation's susceptibility to rising temperatures, shifting precipitation patterns, and intensified extreme weather events accentuates the urgency of understanding the building sector's role in exacerbating or mitigating climate vulnerabilities. Algeria, acknowledging the inevitability of climate change, has initiated resilience and adaptation strategies, not only focusing on emissions reduction but also fortifying structures to withstand the impacts of a changing climate [9,10].

In Figure 1-2, we delve into the environmental impact of the buildings sector in 2022. Buildings contribute significantly to global carbon dioxide (CO2) emissions, constituting 40% of the total. This emphasizes the sector's substantial role in environmental considerations and the urgency of addressing its impact on climate change [5,6].

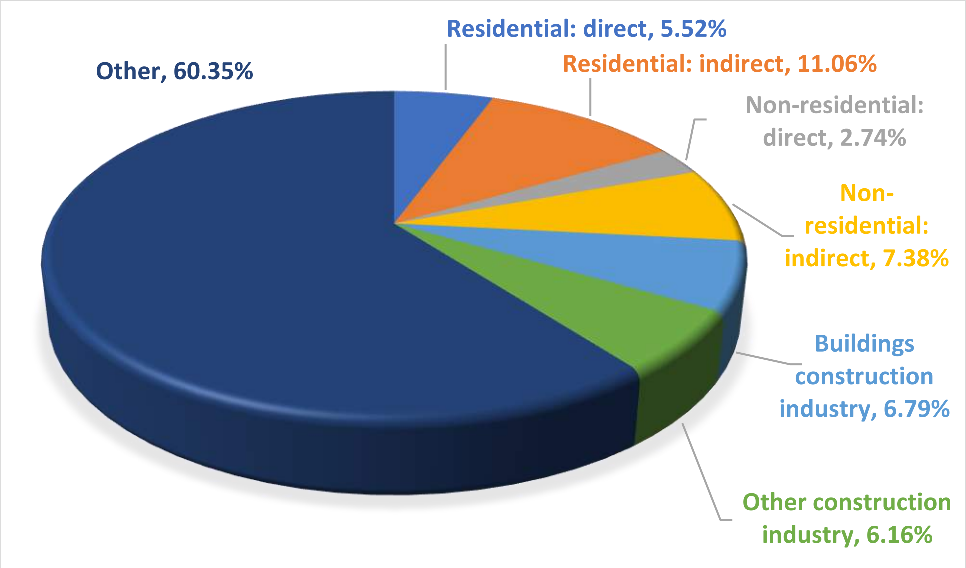


Figure 1-2 Global CO2 emissions from buildings, including embodied emissions from new construction, 2022 [5,6]

Figure 1-1 and 1-2 illustrates the significant impact of the buildings and construction sector on both global final energy consumption and CO2 emissions. It highlights the importance of addressing energy efficiency and sustainability in this sector to mitigate environmental impacts.

1.1.3 Policies to Mitigate Environmental Influence: A Focus on Algeria

Algeria, keenly aware of the environmental imperatives intertwined with the building sector, has strategically formulated policies that seek to align economic development with ecological responsibility, marking concrete steps toward a sustainable future. Spearheading energy efficiency initiatives, the nation emphasizes the adoption of technologies and practices that curtail energy consumption, incentivizing the use of energy-efficient appliances, implementing smart building systems, and encouraging the integration of renewable energy sources into architectural designs [11]. Embracing green building standards, Algeria incorporates stringent environmental criteria into building codes, fostering the development of structures that minimize resource consumption, optimize energy usage, and reduce overall environmental impact [12]. The commitment to renewable energy transcends the energy sector, permeating urban development with active promotion of solar and wind integration into building infrastructure, including solar panels on rooftops, strategically placed wind turbines, and exploration of innovative clean energy solutions [13]. Recognizing the pivotal role of public awareness, Algeria has embarked on comprehensive campaigns to educate the public, architects, and builders about the importance of sustainable practices in the building sector, fostering a culture of environmental consciousness and empowering individuals and organizations to make informed decisions [10]. To assess the efficacy of these policies, Algeria has implemented ongoing monitoring and evaluation mechanisms, conducting regular audits and assessments to gauge their impact on energy consumption, carbon emissions, and overall environmental sustainability within the building sector. As Algeria navigates the intricate landscape of sustainable development, these policies stand as a testament to the nation's commitment to align with the global mission of fostering environmentally responsible practices within the building sector. Through a harmonious blend of regulatory frameworks, technological advancements, and public engagement, Algeria aspires to build not just structures but a lasting legacy of sustainability for future generations.

Several North African nations have placed a greater emphasis on the transition to more sustainable energy systems. All four nations have established renewable energy targets, and two nations—Algeria, and Tunisia—have implemented measures to reduce the carbon intensity of their economies to contribute to the achievement of their nationally determined contributions (NDCs) (Table 1.1). Progress has been hindered in Libya, where the security situation is particularly precarious, and has been inconsistent [14].

Table 1-1 Energy-related plans and commitments by North African countries [14]

Country	National plans and commitments
Algeria	• Aim to reduce greenhouse gas (GHG) emissions by 7% (unconditional) to 22% (conditional), by 2030, compared with a business-as-usual scenario. • The National Program for Renewable Energy and Energy Efficiency sets out a target for renewables to account for 27% of electricity generated by 2030.
Egypt	• The Integrated Sustainable Energy Strategy 2035 sets a target for renewables to make up 42% of the electricity mix by 2035.
Libya	• The Strategic Plan for Renewable Energies, 2018-30 sets a target of reaching 6.6 GW of renewable capacity by 2030.
Tunisia	• Aim to reduce carbon intensity by 13% (unconditional) to 41% (conditional), by 2030 compared with 2010 as base year. • The National Renewable Energy Action Plan 2018 sets out a target for renewables capacity of 3.8 GW by 2030.

1.2 Research Problem

The building sector stands as a significant contributor to global energy consumption, underscoring the imperative of optimizing its energy performance. In a bid to streamline efficient energy management and bolster overall energy efficiency, a focused research initiative has been launched. The primary objective of this comprehensive study is to meticulously characterize the energy performance of local habitats, thereby paving the way for the identification of targeted intervention strategies. By delving into the intricate dynamics of energy consumption within the building sector, this research aims to offer valuable insights that transcend conventional approaches. The overarching goal is to not only assess the current state of energy efficiency but also to lay the groundwork for transformative measures that align with global sustainability objectives.

This research problem is framed within the context of a broader commitment to environmental stewardship and the pressing need to curtail carbon footprints. As the building sector accounts for a substantial share of annual global energy consumption, addressing its energy performance is pivotal in mitigating the environmental impact. Through a systematic exploration of various parameters influencing energy efficiency, this study endeavors to chart a course toward more sustainable living practices. The articulation of this research problem establishes a foundation for future inquiries into the intricacies of energy consumption in local habitats, positioning it as a cornerstone in the pursuit of environmentally conscious and energy-efficient building practices.

1.3 Research Aim and Objectives

In the pursuit of sustainable living practices and comprehensive environmental impact, the research sets out with a multi-faceted aim and a set of detailed objectives:

1.3.1 Aim

The overarching aim of this research is to meticulously assess and elevate the energy performance of both local habitats and educational facilities. With a keen focus on achieving high environmental quality, the research aims to contribute to the broader discourse on sustainable living practices and energy-efficient solutions. This comprehensive goal reflects a commitment to fostering environments that not only optimize energy consumption but also prioritize the overall well-being of occupants and the surrounding ecosystem.

This aim serves as the guiding beacon for the entire research endeavor, directing efforts toward the dual objectives of evaluation and improvement. By harmonizing considerations for energy efficiency with an unwavering commitment to environmental quality, the research aims to lay the groundwork for transformative practices in local habitats and educational institutions. The synthesis of these dual objectives encapsulates a vision of holistic sustainability, where energy-efficient interventions contribute to an enhanced quality of life and a reduced ecological footprint.

1.3.2 Objectives

Objective one: Numerically determine the impact of various parameters:

- ❖ Analyze the influence of climate, construction materials, and envelope on building thermal performance through a rigorous numerical assessment.

Objective two: Develop an energy balance model:

- ❖ Create an advanced energy balance model to precisely quantify the effects of identified parameters on indoor thermal comfort, providing a scientific foundation for subsequent interventions.

Objective three: Evaluate direct and indirect impacts:

- ❖ Conduct a comprehensive assessment of the project's impacts on scientific, socio-economic, and socio-cultural aspects. This includes scrutinizing the scientific advancements generated, as well as the socio-economic and socio-cultural implications of the proposed interventions.

Objective four: Support local authorities in decision-making:

- ❖ Provide scientific and technical expertise to empower local authorities in making informed decisions regarding energy-efficient practices and sustainable living initiatives.

Objective five: Implement ecological village pilot projects:

- ❖ Ensuring the redevelopment of primary schools aligns with high environmental quality standards.

Objective six: Design a school promoting environmental preservation and well-being:

- ❖ Design a school that not only adheres to environmental preservation principles but also prioritizes the health and well-being of occupants. The design will foster eco-citizen values among the new generation.

Objective Seven: Align with national policy on energy transition:

- ❖ Ensure seamless alignment with the national policy encouraging energy transition, contributing to the larger framework of sustainable energy practices at a national level.

1.4 Research Focus and Scope

1.4.1 Description

The research is strategically centered on the village of Khoualed Abdel Hakem in the Wilaya of Ain Temouchent, a community comprising 97 households, around 300 inhabitants, a primary school, and a mosque. This localized focus ensures a deep understanding of the specific dynamics and needs of the community, allowing for targeted interventions that resonate with the unique characteristics of the village.

1.4.2 Scope

❖ Development of a Model for High Environmental Quality:

The primary scope of the research encompasses the creation of a model that integrates high environmental quality standards into the design and functionality of both houses and the local primary school.

❖ Contribution to Decision-Making for Local Authorities:

The project aspires to provide valuable insights to local authorities, aiding them in informed decision-making. By aligning research findings with the needs and aspirations of the community, the research aims to be a pivotal resource for shaping future policies and interventions.

❖ Support for Ecological Village Pilot Project:

The research extends its scope to actively support the ongoing ecological village pilot project. Through targeted interventions and sustainable design proposals, the project aims to enhance the overall ecological footprint of the village.

❖ Alignment with National Policy on Energy Transition:

A key focus is ensuring that the research aligns seamlessly with the national policy on energy transition. By adhering to overarching energy goals set by the nation, the research aims to contribute to the larger framework of sustainable practices at a national level.

❖ Numerical Examination of Parameters for Sustainable Living:

The study will employ rigorous numerical analyses to examine the impact of various parameters on building thermal performance and indoor comfort. This numerical exploration will provide a nuanced understanding of the factors influencing sustainable living practices in the specific context of Khoualed Abdel Hakem.

By concentrating efforts within this specific village context, the research achieves a depth of understanding necessary for impactful and tailored interventions. The outlined scope ensures that the research is not only academically rigorous but also directly applicable and beneficial to the local community and the broader national agenda on energy transition.

1.5 Thesis Structure

This thesis is structured into six comprehensive chapters. Illustrated in Figure 1-3 is the framework of the thesis, offering a clear depiction of the research's evolution through distinct stages.

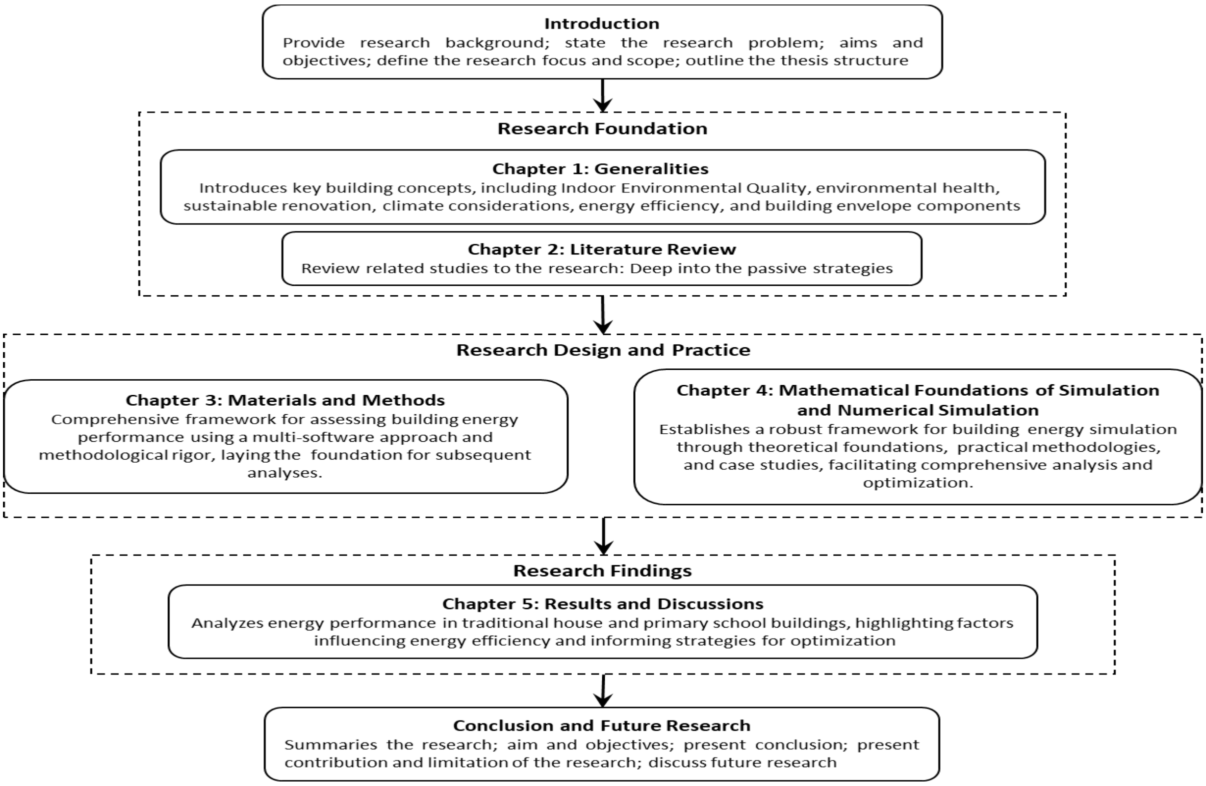


Figure 1-3 Thesis structure

Chapter 1: Introduction and Problematic

This chapter launches a detailed exploration of sustainable practices in Algeria's building sector. It begins with a global overview of energy consumption in buildings, emphasizing Algeria's unique context. Examining environmental impacts and mitigation policies, the chapter sets the stage for the research. Succinctly stating the problem, it outlines the aim and objectives, providing a roadmap. Emphasizing the focus on Khoualed Abdel Hakem, the chapter concludes by outlining the thesis's scope and structure. In essence, Chapter 1 offers a concise introduction, framing the research within global and local contexts while clearly stating the problem and objectives.

Chapter 2: Generalities

This chapter provides a comprehensive introduction to fundamental building concepts. It covers Indoor Environmental Quality indicators, environmental health, and sustainable renovation practices. The chapter also explores climate and thermal comfort indices, energy efficiency, and the significance of building envelope components. This foundational knowledge equips readers with a solid understanding of essential terminology and principles in building design and sustainability.

Chapter 3: Literature Review

In this chapter, the literature review unfolds as a comprehensive exploration of key elements in sustainable building practices. Beginning with an introduction to set the stage, the chapter navigates through critical aspects such as orientation and layout, insulation, shading, and solar control. It delves into the significance of high-performance windows, passive solar heating, and cooling strategies, including the nuanced distinction between daylighting and natural daylight. The review scrutinizes cool roofs, green roofs, natural ventilation, thermal chimneys, earth sheltering, and energy-efficient landscaping as integral components. Each section provides insights into the role of these elements in enhancing energy efficiency and fostering sustainable architectural design. The chapter culminates in a succinct conclusion that synthesizes key findings, offering a valuable overview of the multifaceted strategies underpinning sustainable building practices.

Chapter 4: Materials and Methods

This chapter provides a comprehensive framework for the assessment of energy performance in buildings within the research region. Employing a multi-software approach integrating Meteonorm, Climate Consultant, SketchUp, and TRNSYS, the chapter delineates the methodologies employed for climate characterization, envelope material diagnosis, and determination of thermal comfort limits. Key components include the development of sun shading and psychrometric charts, the evaluation of traditional house and primary school envelope materials and properties, and the establishment of thermal comfort thresholds specific to the study region. The chapter underscores the methodological rigor and holistic approach adopted to investigate energy efficiency in the built environment, laying the foundation for subsequent analyses and findings presented in this thesis.

Chapter 5: Mathematical Foundations of Simulation and Numerical Simulation

Elucidates the theoretical underpinnings and practical methodologies essential for building energy simulation. Through a systematic exposition of mathematical modeling, the chapter delineates the formulation of thermal zones, air nodes, and thermal window models, as well as the incorporation of external and internal shading devices within simulation frameworks. A step-by-step guide to utilizing Meteonorm, Climate Consultant, SketchUp, and TRNSYS for building energy simulation is presented, facilitating a comprehensive understanding of the simulation process. Furthermore, the chapter showcases case studies focusing on traditional house and primary school buildings, providing practical applications of the theoretical concepts elucidated. By integrating mathematical principles with numerical simulation techniques, this chapter establishes a robust framework for analyzing and optimizing building energy performance, thereby laying the groundwork for subsequent investigations presented in this thesis.

Chapter 6: Results and Discussions

Presents the findings and analyses derived from the investigation of energy performance in traditional house and primary school buildings. Within the traditional house context, the effects of insulators of varying thicknesses on indoor environmental conditions and energy consumption are scrutinized, alongside an examination of the impact of glazing configurations on interior environments and energy loads. Similarly, the energy dynamics of primary school buildings are explored, focusing on validations of simulation results, evaluations of shading devices, window-to-wall ratios, glazing types, building envelope adjustments, and the development of an optimized model for primary school energy efficiency. Through a rigorous synthesis of empirical data and theoretical insights, this chapter elucidates key factors influencing building energy performance, facilitating informed discussions on strategies for enhancing energy efficiency in diverse architectural contexts.

Conclusions and Future Research

This section summarizes the research. It presents the findings of the research and the implications. It starts by reviewing the research aims, and objectives. A conclusion with major findings follows, and then it discusses the contribution and limitations of the research. Lastly, potential future research directions are suggested.

2 Generalities

This chapter serves as a foundational introduction to the essential concepts and terminology within the realm of building design and construction. It begins by elucidating Indoor Environmental Quality (IEQ) indicators, emphasizing their pivotal role in ensuring occupant health and well-being. The chapter then delves into the critical intersection of environmental health and building design, highlighting the imperative of sustainable renovation practices. Exploring climate and thermal comfort indices, it elucidates the dynamic relationship between climate conditions and occupant comfort preferences. Energy efficiency and sustainability emerge as central themes, underscoring the importance of minimizing environmental impact while maximizing building performance. Finally, the chapter concludes with an examination of building envelope components, elucidating their role in providing structural integrity, energy efficiency, and thermal comfort. Through this comprehensive overview, readers gain a foundational understanding of key concepts essential for navigating the intricacies of building design and environmental sustainability.

2.1 The Indoor Environmental Quality Indicators

The Indoor Environmental Quality (IEQ) Indicators Chart in Figure 2-1 provides a comprehensive overview of key factors influencing the indoor environment's quality and occupants' well-being. This chart serves as a valuable reference tool for building designers, architects, facility managers, and occupants, highlighting critical aspects such as indoor air quality, thermal comfort, lighting quality, acoustic comfort, and overall comfort and well-being. By presenting these indicators in a concise and organized format, the chart facilitates informed decision-making in building design, operation, and maintenance to create healthier, more comfortable, and productive indoor environments.

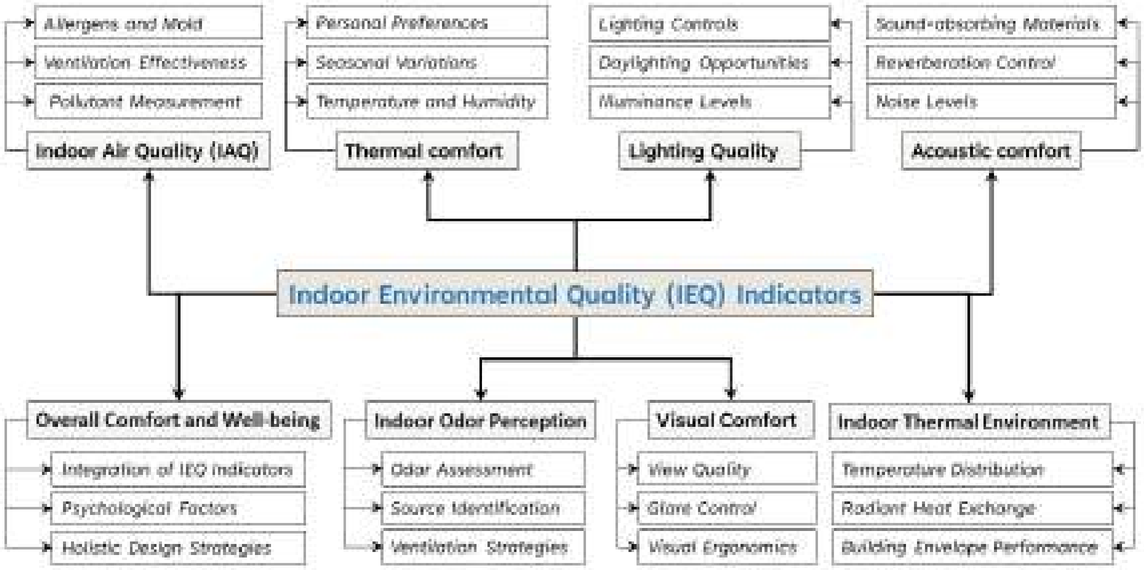


Figure 2-1 Indoor Environmental Quality (IEQ) indicators chart

2.1.1 Indoor Air Quality

Indoor Air Quality (IAQ) is vital for occupants' health and comfort [15]. Measuring pollutants like volatile organic compounds (VOCs), particulate matter, carbon monoxide, and radon is essential [16-20]. Adequate ventilation is crucial for removing contaminants and maintaining oxygen levels [21-23]. Biological pollutants like allergens and mold also impact IAQ and require regular assessment [16,24,25]. By addressing these factors, occupants can enjoy a healthier indoor environment.

2.1.2 Thermal Comfort

Thermal comfort is defined as: "that condition of mind in humans which expresses satisfaction with the thermal environment (ANSI/ASHRAE Standard 55)." To have "thermal comfort" indicates that a person wearing a normal amount of clothing feels neither too cold nor too warm. This can be achieved when the air temperature, humidity and air movement are within a specified range often referred to as the "comfort zone."

The most commonly used indicator of thermal comfort is air temperature – it is easy to use and most people can relate to it. But although it is an important indicator to take into account, air temperature alone is neither a valid nor an accurate indicator of thermal comfort or thermal stress. Air temperature should always be considered concerning other environmental and personal factors [26,27].

The six factors affecting thermal comfort are both environmental and personal. These factors may be independent of each other but together contribute to a person's thermal comfort.

- ❖ Environmental factors: (Air Temperature, Relative Humidity, Mean Radiant Temperature, Air Velocity).
- ❖ Personal factors: (Clothing Insulation, Metabolic Heat).

2.1.2.1 Environmental factors

2.1.2.1.1 Air Temperature

This is the temperature of the air surrounding the body. The comfort low and comfort high temperatures are the primary determinants of the comfort zone, although different sources have slightly different definitions.

the ASHRAE handbook of fundamentals comfort model shows how the comfort zone changes as a function of clothing, i.e. the zone is defined by warmer temperatures in the summer when people are wearing lighter clothes [26-28].

2.1.2.1.2 Relative Humidity

The relative humidity is the ratio of the amount of moisture in the air compared to the maximum amount that the air can hold at that air temperature [29].

2.1.2.1.3 Mean Radiant Temperature

The mean radiant temperature is expressed as the surface temperature and is controlled by enclosure performances. What we experience and feel relating to thermal comfort in the building is related to the influence of surface temperature and the dry air temperature in the space we are in [30].

2.1.2.1.4 Air Velocity

The primary environmental factor for expanding the comfort zone is Air Velocity. Air motion is one of the few ways to produce a cooling effect on the human body.

The most cost-effective cooling strategy is simply to open the windows when outdoor conditions are more comfortable than indoors. By opening windows at night when it is cool and closing them in the morning when outdoors becomes warmer than indoors, the average indoor temperature can be kept cooler than the average outdoor temperature [31].

2.1.2.2 Personal factors

There are two indicators affecting comfort are clothing (CLO factor) and level of physical activity (MET) [32-34].

2.1.2.2.1 Clothing Insulation (CLO)

The amount of clothing people wear is one of the factors affecting human thermal comfort. A person may add layers of clothing if he/she feels cold, or remove layers of clothing if he/she feels warm.

Rating (According to the ASHRAE Standard 55): Indoor winter clothing of long pants and a sweater is about 1.0 CLO while indoor summer clothing of shorts and a light top is 0.5 CLO.

2.1.2.2.2 Work Rate / Metabolic Heat (MET)

The amount of physical activity people engage in is another factor affecting human thermal comfort.

The work or metabolic rate is essential for a thermal comfort assessment. It describes the heat that we produce inside our bodies as we carry out physical activity. The MET rating is a measure of this amount.

Rating (According to the ASHRAE Standard 55): 1.1 MET represents a person sitting and reading. Sleeping is 0.5 MET and normal casual activities around the house throughout the year averages about 1.0 MET for both men and women.

In conclusion, thermal comfort is a key aspect of indoor environmental quality, influencing occupants' well-being and productivity. It involves assessing temperature, humidity, and air movement to ensure occupants' comfort levels are met [35]. Seasonal variations and microclimate conditions within the building must be evaluated to account for changes in weather patterns and localized environmental factors [36]. Additionally, consideration of personal preferences and adaptive strategies, such as adjusting clothing or using fans, plays a crucial role in maintaining thermal comfort for occupants.

2.1.3 Lighting Quality

Assessing lighting quality involves various factors to enhance visual comfort and promote well-being in indoor environments. This includes measuring illuminance levels, glare, and color rendering to support visual tasks effectively and ensure occupant satisfaction [37,38]. Additionally, evaluating natural daylighting opportunities and artificial lighting design is crucial for optimizing lighting conditions and minimizing energy consumption [39,40]. Furthermore, considering lighting controls for energy efficiency and user satisfaction is essential in creating a comfortable and sustainable lighting environment [41,42].

2.1.4 Acoustic Comfort

Enhancing acoustic comfort involves several key steps to create a conducive indoor environment for occupants. This includes evaluating noise levels from both internal and external sources to identify potential sources of disturbance [43,44]. Additionally, assessing reverberation, speech intelligibility, and background noise is essential for understanding the overall acoustic environment and its impact on occupant comfort [45,46] Furthermore, implementing sound-absorbing materials and acoustic design strategies can help minimize disturbances and improve acoustic conditions within indoor spaces [47,48]. By addressing these factors, buildings can promote a more pleasant and productive environment for occupants [49].

2.1.5 Indoor Thermal Environment

Optimizing the indoor thermal environment requires a comprehensive analysis of various factors to ensure occupant comfort and energy efficiency. This includes considering temperature distribution and fluctuations within occupied spaces to identify areas of potential discomfort and inefficiency [50,51]. Additionally, assessing radiant heat exchange and thermal gradients is crucial for understanding heat transfer mechanisms and optimizing heating and cooling systems [52]. Furthermore, the performance of building envelope components plays a significant role in minimizing heat loss or gain and maintaining stable indoor [53,54].

2.1.6 Visual Comfort

Visual comfort in built environments is a crucial aspect of occupant satisfaction and well-being, encompassing various factors that contribute to a pleasant and productive visual experience. Evaluating visual stimuli, including view quality, aesthetics, and access to nature, is essential for creating visually appealing spaces [55,56]. Additionally, considerations such as glare control, daylight availability, and visual ergonomics play significant roles in mitigating discomfort and promoting visual well-being [57,58]. Furthermore, the implementation of design strategies aimed at enhancing visual comfort and minimizing eye strain is crucial for creating optimal visual [59]. By addressing these aspects comprehensively, built environments can foster a sense of comfort and satisfaction among occupants.

2.1.7 Indoor Odor Perception

Indoor odor perception is a critical aspect of occupant comfort and well-being, requiring careful assessment and management to maintain a pleasant indoor environment. This involves evaluating indoor odors, including their sources, intensity, and perception by occupants [60,61]. Identifying potential sources such as cooking, cleaning chemicals, or building materials is essential for understanding and mitigating odor issues [62]. Implementation of ventilation and odor control measures, such as proper ventilation systems and air purifiers, can help maintain a pleasant indoor environment and improve indoor air quality. By addressing these factors comprehensively, buildings can create a more comfortable and enjoyable indoor environment for occupants.

2.1.8 Overall Comfort and Well-being

Enhancing overall comfort and well-being in buildings requires a comprehensive approach that integrates multiple indoor environmental quality (IEQ) indicators to assess occupants' satisfaction and health. This involves considering not only physical factors such as temperature, air quality, and lighting but also psychological factors such as stress levels and perceived control over the indoor environment [63,64]. Implementation of holistic design and operational strategies, including biophilic design elements, access to natural light, and ergonomic furnishings, can promote health, productivity, and overall well-being among occupants [65]. By addressing these factors in tandem, buildings can create environments that support occupants' comfort, satisfaction, and overall quality of life.

These IEQ indicators provide a comprehensive framework for evaluating and optimizing the indoor environment to support occupant health, comfort, and productivity.

2.2 Environmental Health

The chart in Figure 2-2 provides an overview of essential components within the field of environmental health, highlighting key areas of focus such as air and water quality, food safety, waste management, vector control, radiation protection, occupational safety, and climate change adaptation. These elements collectively contribute to safeguarding public health and promoting sustainable living environments.

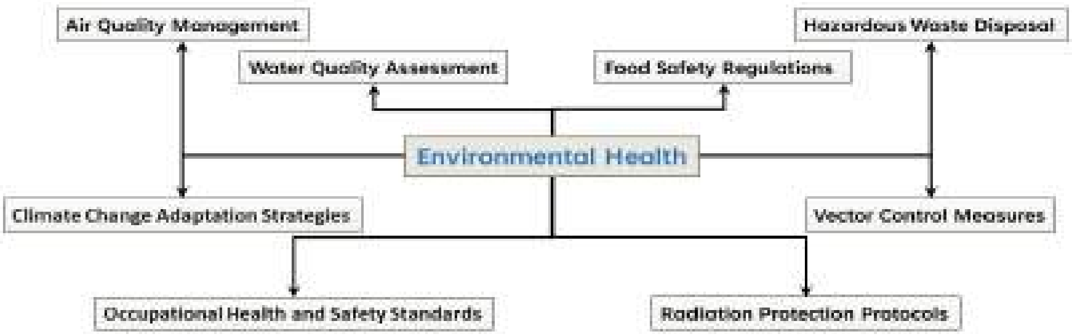


Figure 2-2 Key aspects of environmental health

Environmental health encompasses the assessment and management of various environmental factors that can impact human health and well-being. This field focuses on understanding the interactions between people and their surroundings to prevent disease, promote health, and create sustainable environments. Key aspects of environmental health include:

2.2.1 Air Quality Management

Air Quality Management involves the vigilant monitoring and stringent control of various pollutants, including particulate matter, volatile organic compounds (VOCs), ozone, and nitrogen dioxide. Through comprehensive measures, it aims to maintain clean and healthy environments both indoors and outdoors [66].

2.2.2 Water Quality Assessment

Water Quality Assessment involves meticulous scrutiny aimed at ensuring the safety and purity of drinking water sources. This process entails continuous monitoring for a diverse range of contaminants, including bacteria, heavy metals, pesticides, and chemicals, to safeguard public health and environmental integrity [67].

2.2.3 Food Safety Regulations

Food Safety Regulations encompass a set of stringent measures designed to prevent contamination of food products throughout the entire food supply chain. These regulations aim to ensure safe handling, storage, and preparation of food items to mitigate the risk of foodborne illnesses and safeguard public health [68].

2.2.4 Hazardous Waste Disposal

Hazardous Waste Disposal refers to the systematic and safe management of hazardous materials and wastes to prevent environmental contamination and minimize health risks to communities [69]. This process involves the proper handling, transportation, treatment, and disposal of hazardous substances in accordance with regulatory guidelines and best practices. Effective hazardous waste disposal strategies are essential for protecting both human health and the environment from the adverse effects of toxic substances.

2.2.5 Vector Control Measures

Vector Control Measures involve the implementation of various strategies aimed at controlling vectors such as mosquitoes, rodents, and insects to mitigate the spread of diseases such as malaria, dengue fever, and Lyme disease [70]. These measures encompass a range of interventions including habitat modification, biological control methods, insecticide application, and public education campaigns. By targeting the breeding sites and transmission pathways of disease vectors, vector control efforts aim to reduce the incidence of vector-borne diseases and safeguard public health.

2.2.6 Radiation Protection Protocols

Radiation Protection Protocols entail the monitoring and regulation of exposure to ionizing and non-ionizing radiation sources, such as X-rays, ultraviolet radiation, and electromagnetic fields, to mitigate health risks such as cancer and genetic damage [71]. These protocols involve the establishment of safety standards, dose limits, and protective measures for individuals working with or exposed to radiation in various settings, including medical facilities, industrial workplaces, and environmental contexts. By implementing stringent protocols and guidelines, radiation exposure can be minimized, ensuring the safety and well-being of both workers and the general public.

2.2.7 Occupational Health and Safety Standards

Occupational Health and Safety Standards encompass the establishment and enforcement of regulations to ensure safe working conditions and protect workers from various occupational hazards. These hazards include chemical exposures, physical dangers, and ergonomic risks [72]. By implementing stringent standards, organizations aim to prevent workplace accidents, injuries, and illnesses, promoting employee well-being and productivity. Compliance with these standards often involves conducting risk assessments, providing appropriate training and protective equipment, and fostering a culture of safety within the workplace.

2.2.8 Climate Change Adaptation Strategies

Climate Change Adaptation Strategies involve addressing the health impacts of climate change, which include heat-related illnesses, vector-borne diseases, respiratory ailments, and food and water shortages. These strategies aim to mitigate these impacts through adaptation and mitigation measures [73]. This includes implementing policies and initiatives to enhance resilience to climate-related health risks, such as improving healthcare infrastructure, enhancing early warning systems, promoting sustainable agriculture practices, and reducing greenhouse gas emissions. By proactively addressing the health challenges associated with climate change, communities can better protect public health and build more sustainable and resilient societies.

By addressing these various aspects of environmental health, communities can safeguard public health, promote sustainable development, and create healthier living environments for all individuals.

2.3 Sustainable Renovation of Buildings

Table 2-1 provides an overview of the key concepts associated with sustainable building and renovation. It summarizes the fundamental principles and objectives behind each concept, highlighting their unique characteristics and goals in the context of construction and development projects.

Table 2-1 Overview of sustainable building and renovation concepts

Concept	Sub-Concept	Key Elements
Sustainable Building	Environmental Responsibility	• Energy Efficiency, • Resource Conservation, • Water Efficiency, • Resilience and Adaptation
	Social Equity and Community Engagement	• Healthy Indoor Environment, • Social Equity, • Community Engagement
	Economic Viability	• Lifecycle Considerations, • Economic Prosperity
Renovation	Preservation	• Retaining Original Features, • Safeguarding Historical Significance
	Restoration	• Returning to Original State, • Replicating Historical Details
	Adaptation	• Modifying for Changing Needs, • Repurposing Existing Spaces
	Modernization	• Upgrading Building Systems, • Integrating Sustainable Design
	Renewal	• Revitalizing Neglected Areas, • Stimulating Economic Growth
	Sustainability	• Minimizing Environmental Impact, • Enhancing Indoor Environmental Quality
	Innovation	• Embracing Advanced Technologies, • Streamlining Construction Processes

2.3.1 The Concept of Sustainable Building

Sustainable building, also known as green building or eco-friendly construction, is an approach to designing, constructing, and operating buildings that seeks to minimize environmental impact, conserve resources, promote occupant health and well-being, and enhance long-term economic viability. At its core, sustainable building embodies the principles of environmental responsibility, social equity, and economic prosperity [74-76]. Key aspects of the concept include:

2.3.1.1 Environmental Responsibility

2.3.1.1.1 Energy Efficiency

Energy efficiency is a fundamental aspect of environmental responsibility in sustainable building practices. It involves prioritizing the adoption of design strategies and technologies that minimize energy consumption, leading to reduced operational costs and greenhouse gas emissions. Examples of energy-efficient measures include the integration of passive solar design, efficient lighting systems, and high-performance insulation to optimize building performance and thermal comfort while minimizing reliance on fossil fuels.

2.3.1.1.2 Resource Conservation

Resource conservation is another key component of environmental responsibility in sustainable building. This aspect focuses on minimizing resource consumption and waste generation throughout the building's lifecycle. Sustainable building practices emphasize the selection of environmentally preferable materials, such as recycled or renewable resources, as well as the implementation of efficient construction methods to reduce construction waste and environmental impact.

2.3.1.1.3 Water Efficiency

Water efficiency plays a crucial role in sustainable building design by promoting the responsible use and conservation of water resources. Sustainable buildings incorporate water-saving measures such as low-flow fixtures, rainwater harvesting systems, and drought-resistant landscaping to minimize water consumption and preserve freshwater supplies. By implementing these strategies, sustainable buildings can reduce strain on municipal water systems and contribute to overall water sustainability.

2.3.1.1.4 Resilience and Adaptation

Resilience and adaptation are essential considerations in sustainable building design, particularly in the face of climate change and natural disasters. Sustainable buildings are designed to withstand environmental challenges and adapt to changing conditions, enhancing their longevity and safety. Resilient building features may include flood-resistant design elements, stormwater management systems, and passive heating and cooling strategies to ensure occupant comfort and safety in various environmental scenarios.

2.3.1.2 Social Equity and Community Engagement

2.3.1.2.1 Healthy Indoor Environment

Creating a healthy indoor environment involves designing spaces that prioritize the well-being and comfort of occupants. This includes implementing strategies to improve air quality by minimizing indoor pollutants, ensuring proper ventilation systems, and integrating ergonomic design principles to enhance comfort and productivity. By optimizing factors such as lighting, acoustics, and thermal comfort, sustainable buildings can create environments that support occupants' physical and mental health.

2.3.1.2.2 Social Equity and Community Engagement

Social equity and community engagement are fundamental principles of sustainable building practices. Beyond focusing solely on environmental aspects, sustainable design seeks to address social inequalities and promote inclusivity within communities. This involves engaging stakeholders throughout the design and construction process to ensure that the needs and concerns of all members of society are considered. By fostering collaboration and participation, sustainable buildings can contribute to the creation of more resilient, vibrant, and cohesive communities, where everyone has equitable access to resources and opportunities for a better quality of life.

2.3.1.3 Economic Viability

2.3.1.3.1 Lifecycle Considerations and Economic Prosperity

Sustainable building practices also prioritize economic viability by considering lifecycle considerations and economic prosperity. This involves assessing the environmental, economic, and social impacts of a building throughout its lifecycle, from planning and construction to operation and disposal. By optimizing sustainability across all stages of a building's lifecycle, sustainable buildings can minimize long-term costs, enhance property value, and contribute to the economic prosperity of communities. Additionally, sustainable building practices can create new opportunities for green jobs and industries, further supporting economic growth and development.

2.3.2 The Concept of Renovation

Renovation is the process of restoring or improving the condition of a building, structure, or space to enhance its functionality, aesthetics, and overall value. It involves making modifications, repairs, or upgrades to existing elements while preserving the building's original character or historical significance [77-79]. The concept of renovation encompasses various aspects, including:

2.3.2.1 Preservation

Retaining and safeguarding the original architectural features and historical significance of a building or structure. This aspect of renovation focuses on maintaining the integrity and authenticity of historical buildings, landmarks, or structures, ensuring that their unique character and cultural heritage are preserved for future generations. Preservation efforts often involve careful documentation, conservation, and restoration of original materials and architectural elements, aiming to protect the historical context and significance of the site while allowing it to continue serving its intended function or purpose in contemporary society.

2.3.2.2 Restoration

Returning a building to its original state or replicating historical details through repairs or reconstruction. This aspect of renovation focuses on reviving the original appearance and character of a structure, typically aiming to recreate its historical significance and architectural authenticity. Restoration projects often require meticulous research and analysis to understand the original design, materials, and construction techniques used in the building's creation. Through careful craftsmanship and attention to detail, restoration efforts seek to recreate lost or damaged elements, such as ornamental features, facades, or interior finishes, while adhering to preservation standards and guidelines. The goal is to provide a faithful representation of the building's original appearance while ensuring its structural integrity and longevity for future generations to appreciate and enjoy.

2.3.2.3 Adaptation

Modifying existing spaces to accommodate changing needs or repurposing them for new uses. This aspect of renovation acknowledges that buildings must evolve to meet the evolving needs of users, communities, and society as a whole. Adaptation may involve redesigning interior layouts, reconfiguring room functions, or retrofitting spaces with modern amenities and technologies to enhance functionality and usability. Additionally, adaptation can entail repurposing older structures for new uses, such as converting industrial warehouses into residential lofts, or transforming historic buildings into cultural centers or commercial spaces. By adapting existing buildings to suit contemporary needs and preferences, renovation projects contribute to the efficient use of existing resources and the preservation of architectural heritage while ensuring that buildings remain relevant and valuable assets within their communities.

2.3.2.4 Modernization

Upgrading building systems and integrating sustainable design practices to meet contemporary standards. This aspect of renovation recognizes the need to improve the performance, efficiency, and environmental sustainability of existing structures. Modernization efforts may include replacing outdated mechanical, electrical, and plumbing systems with energy-efficient alternatives, installing smart building technologies for enhanced control and monitoring, and integrating renewable energy systems such as solar panels or geothermal heating and cooling. Additionally, modernization often involves enhancing building envelopes with high-performance insulation and glazing systems to improve thermal comfort and reduce energy consumption. By incorporating sustainable design principles and cutting-edge technologies, modernization not only enhances the functionality and performance of buildings but also reduces their environmental impact, contributing to the long-term sustainability of the built environment.

2.3.2.5 Renewal

Renewal, within the context of renovation, involves revitalizing neglected areas to stimulate economic growth and enhance the quality of life for residents and communities. This aspect of renovation focuses on transforming blighted or underutilized spaces into vibrant, thriving environments that contribute positively to the surrounding community. Renewal projects often include redevelopment initiatives, urban regeneration efforts, and neighborhood revitalization programs aimed at breathing new life into dilapidated or abandoned areas. These projects may involve repurposing vacant buildings for mixed-use developments, creating public green spaces and recreational amenities, and fostering a sense of community through social engagement and cultural activities. By revitalizing neglected areas, renewal efforts can attract investment, create employment opportunities, and improve overall livability, thereby fostering economic prosperity and social well-being in urban and rural areas alike.

2.3.2.6 Sustainability

Sustainability, as a component of renovation, involves integrating environmentally friendly materials and construction practices to minimize the environmental impact of building projects. This aspect of renovation emphasizes the use of renewable resources, energy-efficient technologies, and eco-friendly building materials to reduce carbon emissions, conserve natural resources, and promote ecological balance. Sustainable renovation practices may include incorporating energy-efficient HVAC systems, installing solar panels for renewable energy generation, using recycled or reclaimed building materials, and implementing water-saving fixtures and technologies. Additionally, sustainable renovation projects prioritize indoor environmental quality, aiming to create healthy and comfortable living and working spaces for occupants. By adopting sustainable practices, renovation projects can contribute to mitigating climate change, reducing environmental degradation, and promoting long-term resilience and sustainability in the built environment.

2.3.2.7 Innovation

Embracing advanced technologies and construction methods to enhance project outcomes. This aspect of renovation emphasizes the utilization of cutting-edge tools, techniques, and materials to optimize efficiency, quality, and sustainability in building projects. Innovative renovation practices may include the implementation of Building Information Modeling (BIM) for enhanced project visualization and coordination, the use of prefabricated modular components for streamlined construction processes, and the integration of smart building systems for improved energy management and occupant comfort. Additionally, innovation in renovation may involve the adoption of green building certifications such as LEED (Leadership in Energy and Environmental Design) or WELL Building Standard to ensure high-performance and environmentally conscious building designs. By embracing innovation, renovation projects can achieve higher levels of productivity, cost-effectiveness, and environmental stewardship, ultimately contributing to the advancement of the construction industry and the creation of more sustainable built environments.

Overall, the concept of renovation encompasses a diverse range of approaches and objectives aimed at preserving, adapting, and enhancing the built environment to meet evolving needs and aspirations. Whether restoring a historic landmark, transforming an obsolete structure, or revitalizing a community, renovation plays a vital role in shaping the built environment and contributing to the sustainable development of society.

2.3.3 Sustainable Renovation of Residential and Non-Residential Buildings

The chart provides an overview of various strategies for achieving sustainable renovation in both residential and non-residential buildings. These strategies are organized into categories such as energy-efficient upgrades, renewable energy integration, water conservation measures, material selection and waste management, indoor environmental quality enhancement, adaptation to climate change, adaptive reuse and historic preservation, accessibility and universal design, community engagement and social equity, life cycle assessment and performance monitoring. Each category includes specific measures and practices aimed at minimizing environmental impact, enhancing occupant well-being, and promoting long-term sustainability in building renovation projects.

Figure 2-3 Strategies for sustainable renovation of buildings

Sustainable renovation involves upgrading residential and non-residential buildings in an environmentally friendly and resource-efficient manner, aiming to minimize environmental impact and enhance occupant comfort and well-being. This approach encompasses various strategies and practices tailored to improve energy efficiency, reduce carbon footprint, enhance indoor environmental quality, and promote overall sustainability [80-82]. Key elements of sustainable renovation include:

2.3.3.1 Energy-Efficient Upgrades

Implementing measures such as insulation, high-performance windows, energy-efficient heating, ventilation, and air conditioning (HVAC) systems, and renewable energy technologies to reduce energy consumption and carbon emissions.

2.3.3.2 Renewable Energy Integration

Integration of renewable energy sources such as solar panels, wind turbines, and geothermal systems to generate clean and sustainable energy onsite, reducing reliance on fossil fuels and contributing to a greener energy mix.

2.3.3.3 Water Conservation Measures

Adoption of water-efficient fixtures, rainwater harvesting systems, greywater recycling, and low-flow plumbing fixtures to minimize water consumption, preserve freshwater resources, and reduce strain on municipal water supplies.

2.3.3.4 Material Selection and Waste Management

Utilization of eco-friendly and sustainable building materials with low embodied energy and minimal environmental impact, along with proper waste management practices to minimize construction waste and promote recycling and reuse of materials.

2.3.3.5 Indoor Environmental Quality Enhancement

Improving indoor air quality through proper ventilation systems, use of low-VOC paints and finishes, and incorporation of daylighting and natural ventilation strategies to enhance occupant health, comfort, and productivity.

2.3.3.6 Adaptation to Climate Change

Incorporating climate-resilient design features such as flood-resistant construction, stormwater management systems, and passive design strategies to mitigate the impacts of extreme weather events and future climate change

2.3.3.7 Adaptive Reuse and Historic Preservation

Preservation and adaptive reuse of existing structures and heritage buildings to conserve embodied energy, preserve cultural heritage, and minimize the environmental impact associated with new construction.

2.3.3.8 Accessibility and Universal Design

Ensuring buildings are accessible to people of all ages and abilities by incorporating universal design principles and accessible features such as ramps, elevators, and barrier-free entrances.

2.3.3.9 Community Engagement and Social Equity

Involvement of local communities and stakeholders in the renovation process, ensuring inclusivity, accessibility, and social equity, and addressing the needs and preferences of diverse user groups.

2.3.3.10 Life Cycle Assessment and Performance Monitoring

Conducting life cycle assessments to evaluate the environmental impact of renovation projects from cradle to grave, and implementing performance monitoring systems to track energy consumption, indoor environmental quality, and overall sustainability performance over time.

By incorporating these sustainable renovation strategies, both residential and non-residential buildings can be transformed into healthier, more energy-efficient, and environmentally responsible spaces, contributing to the transition towards a more sustainable built environment.

2.4 Climate and Thermal Comfort Indices

2.4.1 Climate

Climate has a major impact on the energy consumption in the buildings. Studying climate data helps inform and evaluate the design of both passive and active strategies. This section delves into the intricate aspects of climate, encompassing its classification, thermal comfort indices, and the analysis of bioclimatic charts [83].

- *Definition of Climate:* Climate encompasses the long-term atmospheric conditions, including temperature, humidity, precipitation, wind patterns, and solar radiation, that prevail in a specific region over an extended period [84].
- *Impact on Energy Consumption:* The climate has a profound impact on the energy consumption of buildings, influencing heating, cooling, and ventilation requirements. Understanding local climate conditions is essential for designing energy-efficient and sustainable buildings [85].
- *Importance of Climate Study:* Thorough analysis of climate data is crucial for architects and engineers to make informed decisions during the design process. By studying climate patterns, designers can optimize building performance, minimize energy consumption, and enhance occupant comfort and well-being [86].

2.4.2 Climate Classification

Climate classification is a systematic method used to categorize and understand the diverse climatic conditions observed across the globe. By classifying climates, researchers, planners, and architects can better comprehend regional weather patterns, which is crucial for various applications such as agriculture, urban planning, and building design [83].

2.4.2.1 Importance of Climate Classification

Understanding climate classification systems allows for better planning and decision-making in areas such as agriculture, urban planning, and building design. By categorizing climates based on common characteristics such as temperature, precipitation, and humidity, professionals can tailor strategies and interventions to suit specific climatic conditions, thereby optimizing resource allocation and improving resilience to climate-related challenges [87,88].

2.4.2.2 Common Climate Classification Systems

The section provides a succinct overview of three prominent climate classification systems: Köppen, ASHRAE, and Thornthwaite. Köppen's system categorizes climates based on temperature and precipitation characteristics, while ASHRAE focuses on HVAC standards for different climate zones. Thornthwaite's approach emphasizes moisture availability. Each system offers unique insights into global climate patterns, aiding researchers and planners in addressing environmental challenges. These classifications facilitate the understanding of temperature, precipitation, and moisture patterns worldwide, guiding decisions related to land use, resource management, and infrastructure development.

2.4.2.2.1 Köppen Climate Classification

Developed by climatologist Wladimir Köppen in the early 20th century, the Köppen climate classification system is one of the most widely used methods for categorizing climates based on temperature and precipitation patterns. Köppen's system results in a hierarchical classification scheme that assigns a unique code to each climate type, with major groups including tropical, dry, temperate, continental, and polar. These groups have further subdivisions based on seasonal variations and precipitation characteristics [87-89].

Additionally, the Köppen Climate Classification system, developed by German climatologist Wladimir Köppen and later modified by his collaborator Rudolf Geiger, categorizes climates based on temperature, precipitation, and seasonal variations. This classification assigns unique codes to different climate types, such as tropical (A), dry (B), temperate (C), continental (D), polar (E), and highland (H), with further subdivisions based on precipitation and temperature patterns.

Figure 2-4 illustrates the world map of the Köppen-Geiger Climate Classification, showcasing the distribution of various climate types across the globe according to the Köppen-Geiger classification system. This map visually represents the diversity of climates worldwide, delineating distinct regions characterized by specific temperature and precipitation patterns. Such visualizations are invaluable for understanding global climate variations and their implications for various human activities, including agriculture, ecology, and urban planning [90].

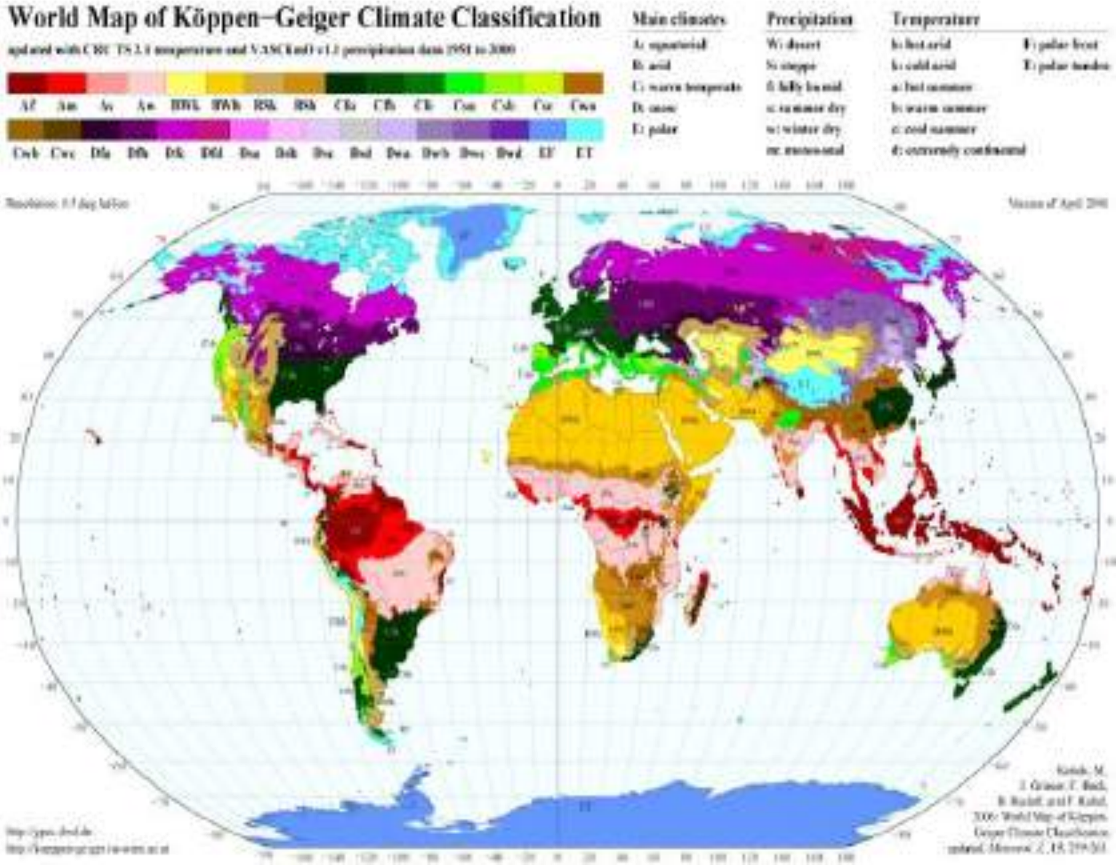


Figure 2-4 World map of the Köppen-Geiger climate classification [90]

2.4.2.2.2 ASHRAE Climate Zones

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) has developed climate zone maps tailored to aid in the design and implementation of heating, ventilation, and air conditioning (HVAC) systems. These maps, specific to the United States, rely on temperature data, humidity levels, and other climatic factors to delineate distinct climate zones. By utilizing ASHRAE's climate zones, engineers and designers can select suitable HVAC equipment and insulation levels, ensuring optimal thermal comfort and energy efficiency in buildings [91,92].

ASHRAE offers a comprehensive classification of climate zones worldwide through the ANSI/ASHRAE 169-2020 standard. Illustrated in Figure 2-5, this classification provides a visual representation of diverse climatic regions across the globe, with each zone characterized by unique temperature and humidity attributes. Such classifications support various applications, including building design and energy efficiency assessments, aiding architects, engineers, and researchers in the built environment [93]. Further details of the ANSI/ASHRAE climate zones classification are outlined in Table 2-

2, listing the different zones alongside their respective identifiers. This systematic approach facilitates easy reference and comparison of climate conditions, furnishing valuable insights for professionals in the architecture, engineering, and research fields. Overall, ASHRAE's climate zones classification stands as a pivotal tool for comprehending and analyzing climatic variations worldwide [94,95].

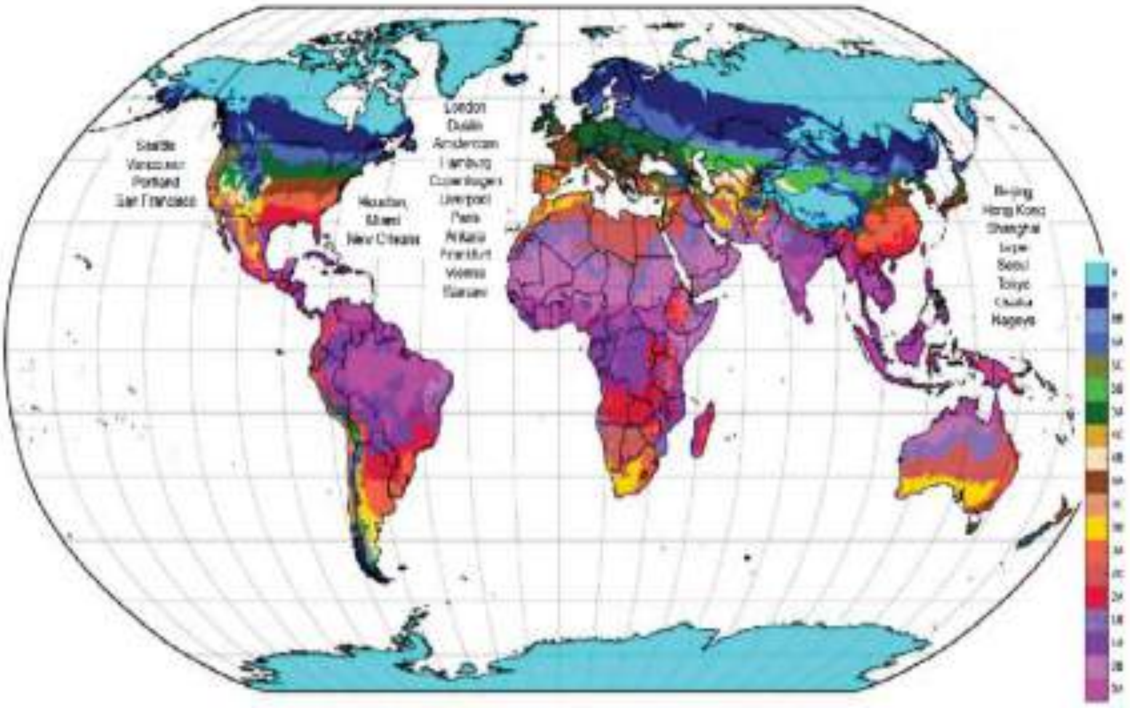


Figure 2-5 ANSI/ASHRAE 169-2020 world climate zones map [93]

Table 2-2 ANSI/ASHRAE climate zones classification [94,95]

Climate zone	**Climate type**	**Climate zone**	**Climate type**
1A	Very Hot-Humid	4C	Mixed-Marine
1B	Very Hot-Dry	5A	Cool-Humid
2A	Hot-Humid	5B	Cool-Dry
2B	Hot-Dry	5C	Cool-Marine
3A	Warm-Humid	6A	Cold-Humid
3B	Warm-Dry	6B	Cold-Dry
3C	Warm-Marine	7	Very Cold
4A	Mixed-Humid	8	Subarctic
4B	Mixed-Dry		

2.4.2.2.3 Thornthwaite Climate Classification

The Thornthwaite climate classification system, conceived by climatologist C.W. Thornthwaite, centers on moisture availability and evapotranspiration rates, offering insights into the water balance of diverse regions. By calculating potential evapotranspiration and moisture deficits, this classification scheme categorizes climates, providing essential information for agricultural planning, water resource management, and ecological understanding [89,96].

Utilizing the concept of potential evapotranspiration (PET), Thornthwaite's method estimates moisture levels, employing the Thornthwaite Moisture Index (TMI) as a pivotal indicator. This index delineates climates from very humid to extremely arid, aiding in comprehending global moisture patterns and their ramifications for various sectors such as agriculture, water management, and urban planning. Figure 2-6 visually portrays Thornthwaite's global moisture regions, facilitating a clear understanding of moisture availability across diverse climates and informing decision-making processes across multiple industries [97,98].

Additionally, Table 2-3 presents the Thornthwaite Moisture Derived Climate Types alongside their corresponding moisture index ranges. These ranges signify the abundance or limitation of moisture in specific climates, offering valuable insights into environmental and ecological processes. By categorizing climates based on their moisture characteristics, this classification system aids researchers and practitioners in comprehensively studying and addressing environmental challenges.

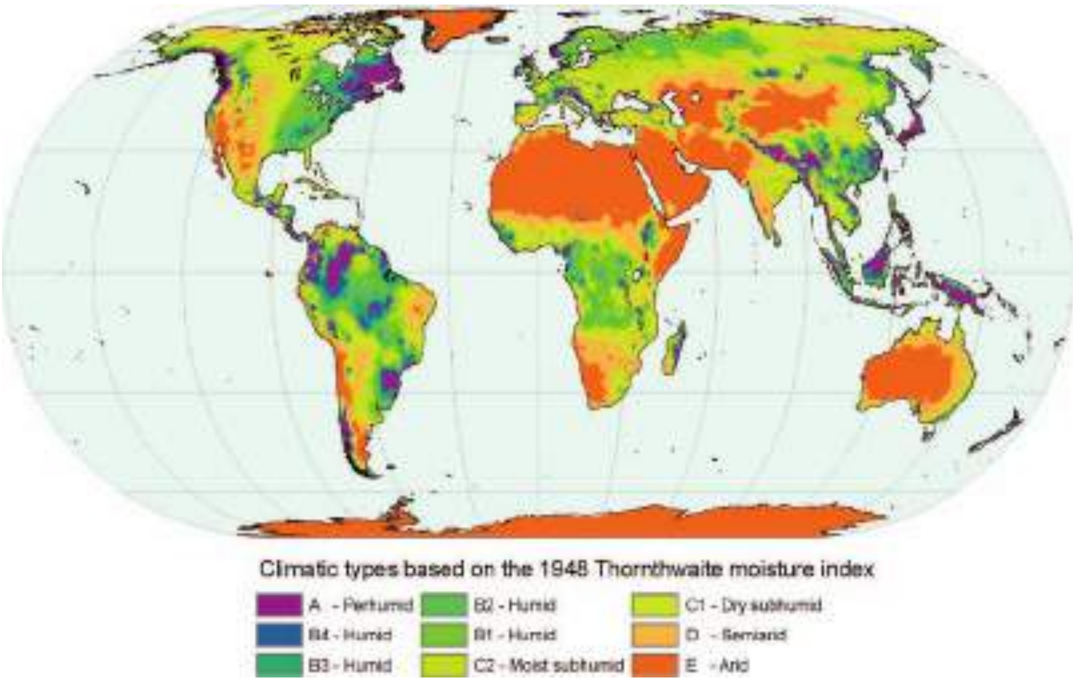


Figure 2-6 Global Thornthwaite moisture regions [98]

Table 2-3 Thornthwaite moisture derived climate types [98]

Climatic type		Moisture index
A	Per humid	100 and above
B_4	Humid	80 to 100
B_3	Humid	60 to 80
B_2	Humid	40 to 60

B_1	Humid	20 to 40
C_2	Humid	0 to 20
C_1	Humid	-20 to 0
D	Semiarid	-40 to -20
E	Arid	-60 to -40

By comparing all the methods, it can be seen that the Koppen and ASHRAE classified the climate based on the annual and monthly averages of temperature and precipitation, while, Thornthwait selected seasonal precipitation and thermal efficiency as bases for climate classification [83].

2.4.2.3 Significance and Applications

Climate classification systems play a vital role in various fields, including agriculture, forestry, urban planning, and building design. By providing a standardized framework for understanding climatic conditions, these classification systems enable researchers and practitioners to make informed decisions and develop appropriate strategies to address climate-related challenges. In the context of building design, climate classification helps architects and engineers optimize energy efficiency, thermal comfort, and sustainability by tailoring design solutions to local climate conditions [87,83].

2.4.3 Bioclimatic Chart Analysis

Bioclimatic chart analysis is a method used in architectural and environmental design to assess and optimize building performance based on climatic data. By utilizing bioclimatic charts, designers can evaluate the interaction between building design, local climate conditions, and human comfort requirements. These charts provide graphical representations of climatic parameters such as temperature, humidity, solar radiation, and wind speed, allowing designers to make informed decisions regarding passive design strategies, energy efficiency measures, and thermal comfort enhancements [99].

2.4.3.1 Givoni's Bioclimatic Chart

Developed by architect and researcher, Baruch Givoni, Givoni's bioclimatic chart is a graphical tool that illustrates the relationship between indoor comfort conditions and external climatic factors. The chart typically depicts temperature and humidity ranges associated with thermal comfort zones for passive design strategies such as natural ventilation, solar shading, and thermal mass utilization. By overlaying climatic data onto Givoni's chart, designers can identify suitable passive design strategies to enhance indoor thermal comfort while minimizing energy consumption [100].

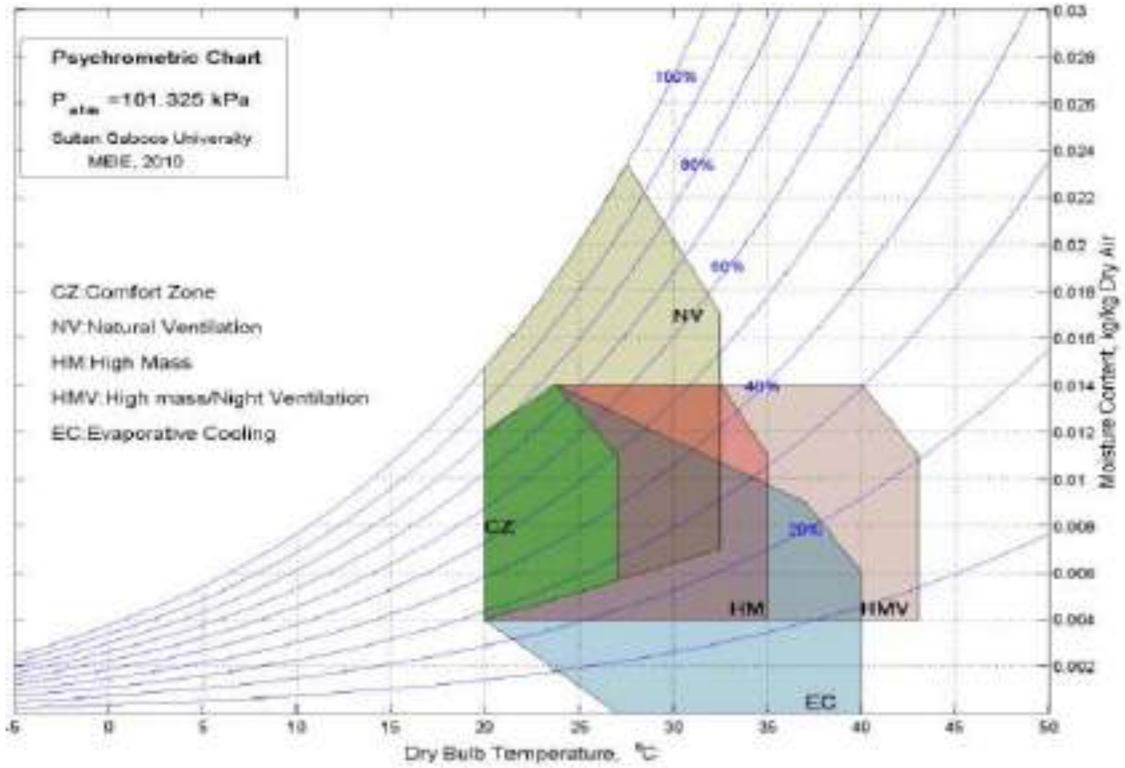


Figure 2-7 Givoni's bioclimatic chart [101]

Figure 2-7 illustrates Givoni's Bioclimatic Chart, a graphical representation of various climatic parameters that influence thermal comfort and energy performance in architectural design. The chart is divided into zones delineating different climatic conditions based on temperature, humidity, and solar radiation data. Each zone corresponds to specific strategies for passive design interventions aimed at optimizing indoor environmental quality and reducing energy demand for heating and cooling [101].

2.4.3.2 Olgyay's Bioclimatic Chart

Proposed by American architect Victor Olgyay in his seminal work "Design with Climate," Olgyay's bioclimatic chart provides a visual representation of climatic data tailored to specific geographic regions. The chart integrates temperature, humidity, and solar radiation data to delineate climatic zones and identify opportunities for passive heating, cooling, and daylighting strategies. Olgyay's chart emphasizes the importance of context-specific design solutions that respond to local climate conditions while promoting sustainability and occupant comfort [102].

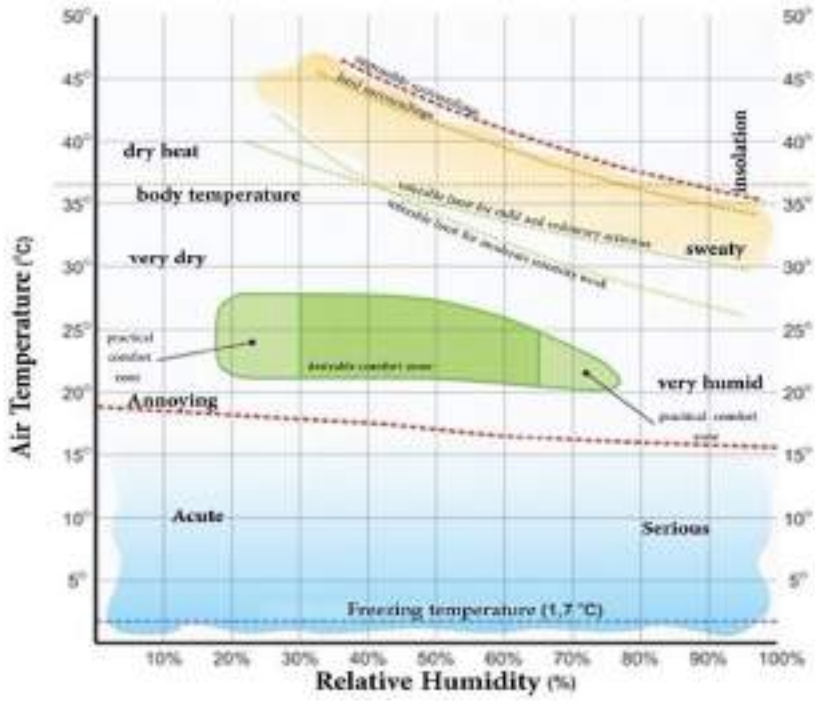


Figure 2-8 Olgyay's bioclimatic chart [103]

Olgyay's Bioclimatic Chart, as referenced in [103] illustrates the relationship between temperature and humidity to determine optimal passive design strategies for thermal comfort and energy efficiency as depicted in Figure 2-8. This chart assists architects and designers in selecting appropriate building orientations, shading devices, and natural ventilation strategies according to specific climatic conditions.

2.4.3.3 Szokolay Bioclimatic Chart

The Szokolay bioclimatic chart is a tool developed by Australian architect and researcher, Bojan Szokolay, to aid in the design of energy-efficient and environmentally sustainable buildings. Similar to other bioclimatic charts, Szokolay's chart incorporates climatic data to inform architectural design decisions related to thermal comfort, daylighting, and ventilation strategies. The chart emphasizes the integration of passive design principles with active energy systems to achieve optimal building performance in diverse climatic contexts [104].

2.4.3.4 Significance and Applications

Bioclimatic chart analysis serves as a valuable tool for architects, engineers, and building designers seeking to create environmentally responsive and energy-efficient buildings. By integrating climatic data into the design process, professionals can optimize building performance, reduce reliance on mechanical systems, and mitigate the environmental impact of construction. Bioclimatic chart analysis facilitates the development of contextually appropriate design solutions that prioritize occupant comfort, health, and well-being while promoting sustainability and resilience in the built environment [105,106].

2.4.4 Thermal comfort indices

Thermal comfort indices, such as the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) metrics, pioneered by Prof. Ole Fanger, are fundamental tools in assessing and maintaining indoor environmental quality. Developed in the 1960s, the PMV model offers a comprehensive framework for quantifying the average thermal sensation experienced by individuals within indoor environments. It considers multiple physical parameters, including air temperature, air velocity, mean radiant temperature, relative humidity, clothing insulation, and activity level, to provide a nuanced understanding of thermal comfort [83].

Thermal comfort, as defined by ASHRAE, encompasses satisfaction with the thermal environment and is intricately tied to the energy required for heating or cooling buildings. This relationship arises from the interplay between the heat generated by occupants' metabolic processes and various environmental factors. These factors include personal attributes like activity level, metabolic rate, clothing, age, gender, and nutrition, as well as environmental conditions such as air temperature, mean radiant temperature, humidity, and air velocity. Metabolic rate, typically measured in 'met' units per unit of skin area ($1.8m^2$), varies depending on factors like diet and activity level, with a resting body generally dissipating around 80W of heat [83,107]. Figure 2-9 illustrates the metabolic rate (met) of different activities, providing insight into the varying levels of heat generation associated with different tasks.

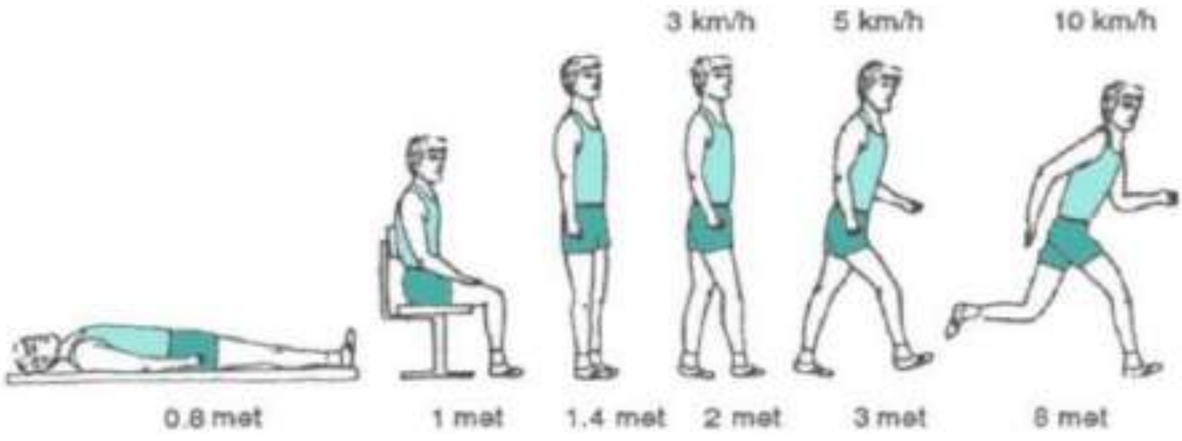


Figure 2-9 Metabolic Rate (met) of various activities figure [83]

Clothing significantly influences thermal comfort by providing insulation. The 'Clo' unit quantifies this insulation, with one Clo representing the amount of insulation required to maintain comfort at 21°C, similar to office worker attire [83,107] Figure 2-10 displays the insulation values (Clo) of typical combinations of clothing, offering a visual representation of the varying levels of insulation provided by different types of attire.

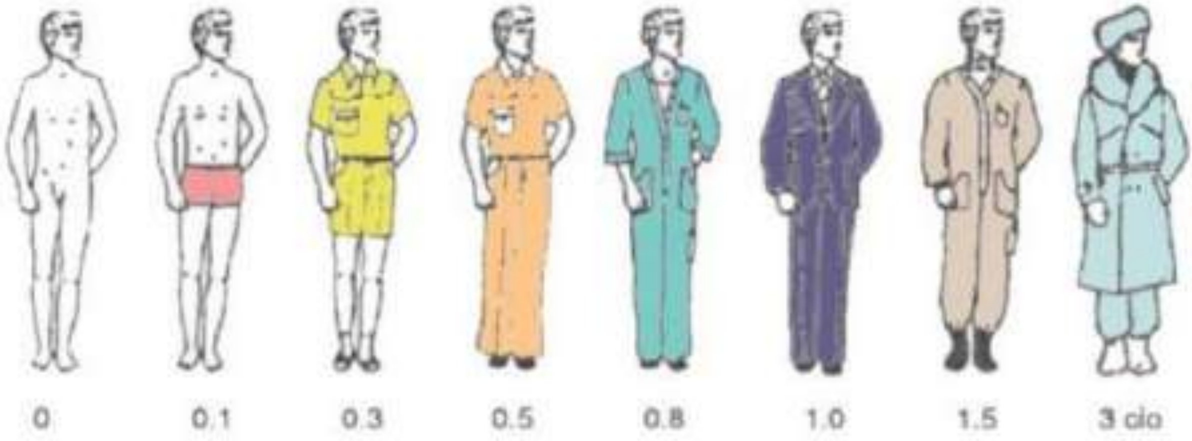


Figure 2-10 Metabolic Rate (met) of various activities figure [83]

The PMV model produces a numerical index ranging from -3 to +3, with 0 representing a neutral thermal sensation. This index enables designers and engineers to assess thermal comfort levels accurately and optimize indoor environmental conditions accordingly. Additionally, the PMV model demonstrates flexibility and applicability across various building types and accounts for individual differences in thermal perception, ensuring that predicted thermal sensations align with occupants' diverse needs and preferences [108-110].

Complementing the PMV model, the Predicted Percentage of Dissatisfied (PPD) model estimates the percentage of occupants likely to feel dissatisfied with the thermal environment based on PMV values and statistical data on human comfort preferences. Unlike the PMV model, which focuses on predicting average thermal sensations, the PPD model considers individual comfort preferences and local discomfort factors, such as draughts, to provide insights into potential dissatisfaction levels among occupants [110,111].

The application of these thermal comfort indices is paramount in the design, operation, and management of heating, ventilation, and air conditioning (HVAC) systems in buildings. Architects, engineers, and building managers rely on PMV and PPD assessments to optimize indoor thermal conditions, ensuring occupant satisfaction, productivity, and well-being. By leveraging these indices, stakeholders can make informed decisions regarding building design, HVAC system optimization, and energy efficiency strategies, ultimately contributing to the creation of healthier and more comfortable indoor environments.

2.5 Energy Efficiency and Sustainability

In the buildings we find today, there is an increasing demand for buildings that prioritize energy efficiency and adhere to environmentally sustainable design principles. This concept of sustainable architecture encompasses a wide array of considerations, including energy, water, land, and material conservation, as well as addressing environmental pollution and enhancing the quality of indoor and outdoor environments. Given this context, a comprehensive review of recent advancements in building envelope components and their impact on overall energy efficiency is essential [112].

The enhancement of building energy efficiency can be achieved through the implementation of active or passive energy-efficient strategies. Active strategies typically involve improvements to heating, ventilation, and air conditioning (HVAC) systems, as well as lighting solutions, among others. Conversely, passive strategies focus on optimizing building envelope elements to reduce energy consumption. Notably, there has been a resurgence of interest in passive building energy efficiency strategies, which are viewed as effective means to address the challenges posed by energy scarcity and environmental degradation [112,113].

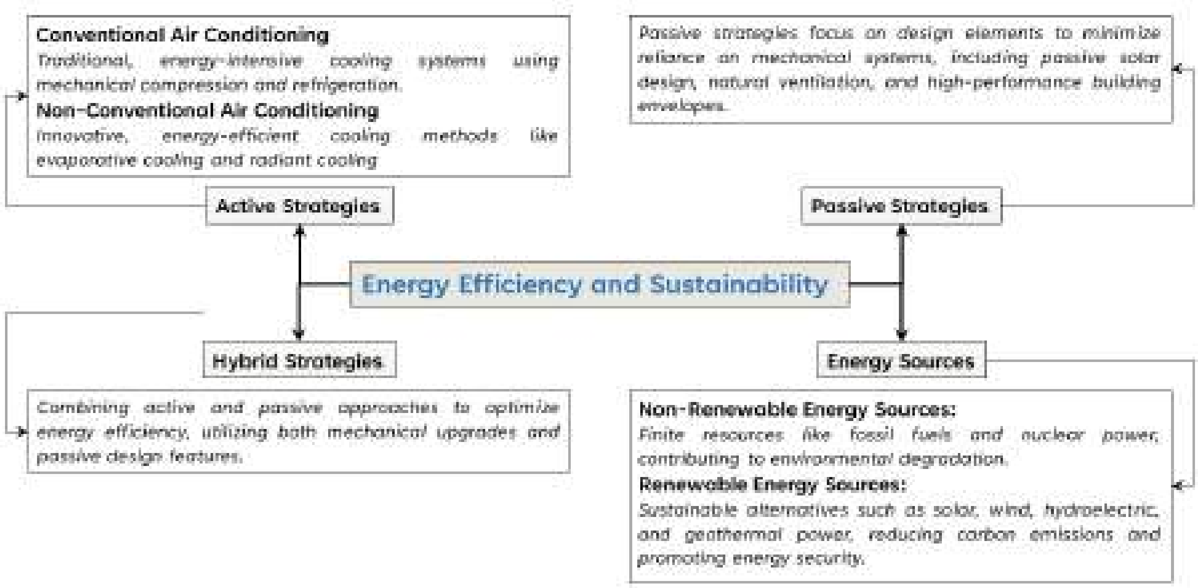


Figure 2-11 Energy efficiency strategies: Active, Passive, Hybrid, and Energy sources

The Figure 2-11 delineates various strategies and energy sources crucial for enhancing energy efficiency and sustainability in buildings. It begins with Active Strategies, encompassing Non-Conventional and Conventional Air Conditioning methods, which optimize heating, ventilation, and air conditioning (HVAC) systems and electrical lighting for energy efficiency. Passive Strategies focus on enhancing building envelope elements, while Hybrid Strategies combine elements of both active and passive approaches. Lastly, Energy Sources are divided into Non-Renewable, such as fossil fuels, and Renewable sources like solar and wind energy, crucial for sustainable building practices.

This chart, illustrated in Figure 2-12, outlines strategies for regulating indoor environments in buildings, categorized into Active, Hybrid, and Passive approaches. Active strategies encompass traditional and innovative air conditioning systems, while Hybrid strategies integrate active and passive methods for enhanced efficiency. Passive strategies rely on design elements and natural processes to minimize energy consumption and optimize comfort levels without extensive mechanical intervention.

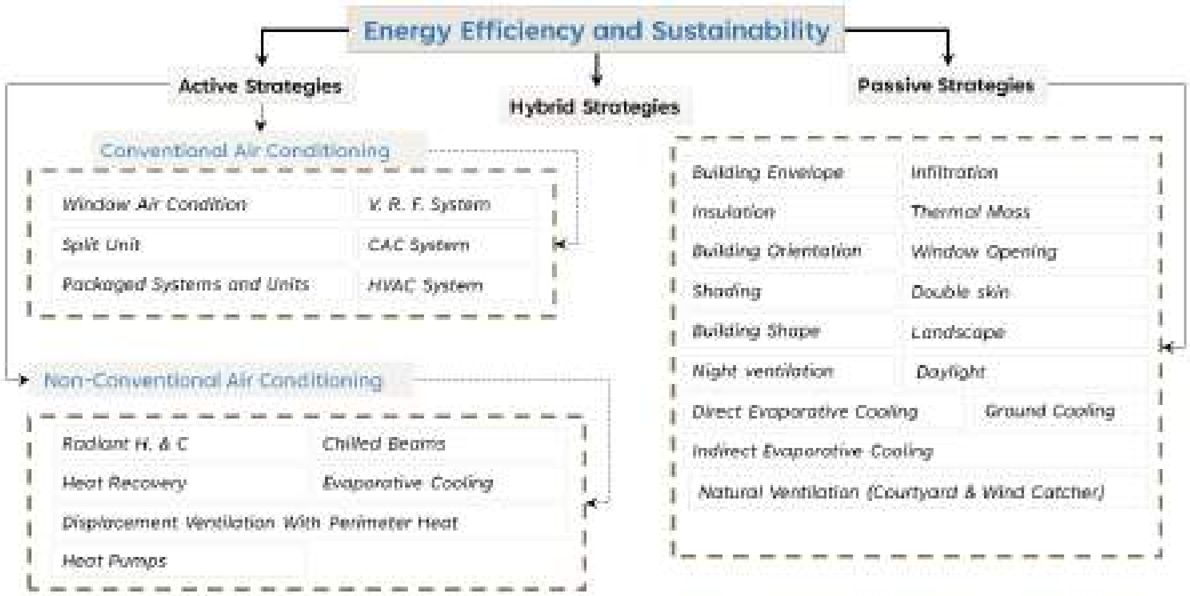


Figure 2-12 Building environmental control strategies

2.5.1 Active Strategies

2.5.1.1 Conventional Air Conditioning

Conventional air conditioning refers to traditional systems that rely on mechanical compression and refrigeration cycles to provide cooling. These systems are widely used for maintaining comfortable indoor temperatures in various settings. However, their reliance on energy-intensive processes makes them significant contributors to energy consumption and environmental pollution [114,115].

Figure 2-13 Overview of conventional air conditioning systems: (Fan, Window AC, Split AC, Packaged AC, Central AC chiller and Variable Refrigerant Flow (VRF) system) [83]

The following are common types of conventional air conditioning systems:

- *Active Ventilation:* This system involves the use of mechanical fans or blowers to circulate air within a building, facilitating air exchange and maintaining indoor air quality [116].
- *Window Air Conditioners:* Window units are standalone systems installed in windows or through walls to cool individual rooms. They consist of an indoor unit containing the cooling components and an outdoor unit for heat dissipation [117].
- *Split Units:* Split air conditioning systems comprise separate indoor and outdoor units connected by refrigerant lines. They offer flexibility in installation and are suitable for cooling single or multiple rooms [118,119].
- *Packaged Systems and Units:* Packaged air conditioners contain all components, including the compressor, condenser, and evaporator, within a single unit. They

are commonly used in commercial buildings and residential properties with limited indoor space [120].

- *Variable Refrigerant Flow System (VRF):* VRF systems use advanced technology to regulate the flow of refrigerant to individual indoor units, allowing for precise temperature control and energy efficiency [121].
- *Central Air Conditioning:* Centralized systems distribute cooled air through ductwork to various rooms within a building. They are commonly used in larger buildings and offer consistent cooling throughout the space [122].
- Heating, Ventilating, and Air Conditioning (HVAC) Systems: HVAC systems integrate heating, ventilation, and air conditioning functions to provide comprehensive climate control. They are versatile systems capable of maintaining comfortable indoor environments year-round [123].

While conventional air conditioning systems are effective at providing cooling, their energy consumption and environmental impact highlight the need for alternative, more sustainable cooling solutions.

2.5.1.2 Non-Conventional Air Conditioning

Non-conventional air conditioning refers to innovative approaches aimed at achieving energy efficiency and environmental sustainability in cooling systems. These methods prioritize minimizing energy consumption and reducing environmental impact while maintaining indoor comfort levels. Non-conventional air conditioning systems encompass a range of technologies and strategies that deviate from traditional mechanical compression and refrigeration cycles.

The following are examples of non-conventional air conditioning systems:

- *Radiant Heating and Cooling:* Radiant systems use radiant panels or tubes installed in ceilings, walls, or floors to heat or cool indoor spaces. They transfer heat directly to occupants and objects, offering efficient and comfortable climate [124].
- *Displacement Ventilation with Perimeter Heat:* This system introduces cool air at low velocities near the floor, displacing warmer air upwards and promoting natural convection. Perimeter heating elements may be used to offset heat losses near exterior walls, improving thermal comfort [125].
- *Chilled Beams:* Chilled beams are passive cooling devices installed in ceilings to cool indoor spaces using chilled water. They operate quietly and efficiently, providing localized cooling without the need for mechanical fans [126].

- ❖ *Heat Recovery:* Heat recovery systems capture waste heat from various sources, such as exhaust air or equipment, and reuse it to preheat or precool incoming air. This reduces the energy required for conditioning outdoor air, improving overall system efficiency [127].
- ❖ *Evaporative Cooling:* Evaporative cooling systems use the natural process of evaporation to cool outdoor air before it enters a building. They are particularly effective in dry climates and can significantly reduce energy consumption compared to conventional air conditioning [128].
- ❖ *Heat Pumps:* Heat pump systems utilize refrigeration cycles to transfer heat between indoor and outdoor environments. They can provide both heating and cooling by extracting heat from outdoor air, water, or the ground and transferring it indoors or vice versa [129].

These non-conventional air conditioning systems offer sustainable alternatives to traditional cooling methods, helping to minimize energy consumption, reduce greenhouse gas emissions, and create healthier indoor environments. By incorporating innovative technologies and strategies, buildings can achieve greater energy efficiency and environmental resilience while ensuring occupant comfort.

2.5.2 Passive Strategies

Passive strategies for enhancing energy efficiency leverage design elements to minimize reliance on active mechanical systems. These approaches capitalize on natural resources such as sunlight, wind, and thermal mass to regulate indoor temperatures and improve occupant comfort without mechanical intervention.

Passive strategies encompass a range of techniques, including solar and thermal control strategies. These strategies focus on optimizing building design elements to harness natural energy sources effectively [112,130,131].

2.5.2.1 Building Envelope

The outer shell of a building, including walls, roofs, windows, and doors, which separates the indoor environment from the external surroundings and influences heat transfer, insulation, and energy efficiency [112].

2.5.2.2 Infiltration

The unintended or uncontrolled flow of air into a building through cracks, gaps, or openings in the building envelope, which can impact indoor air quality, comfort, and energy efficiency [112].

2.5.2.3 Thermal Insulation
Materials or techniques used to reduce heat transfer between the interior and exterior of a building, minimizing heat loss in winter and heat gain in summer, thus improving energy efficiency and comfort [132].

2.5.2.4 Building Orientation
The positioning of a building relative to the sun's path, prevailing winds, and other environmental factors to optimize natural lighting, solar heat gain, and natural ventilation, enhancing energy efficiency and occupant comfort [133].

2.5.2.5 Shading
Techniques such as overhangs, awnings, louvers, or vegetation used to block or diffuse direct sunlight, reducing solar heat gain, glare, and cooling loads, thus improving indoor comfort and energy efficiency [134].

2.5.2.6 Building Shape
The form or configuration of a building, which can influence its exposure to solar radiation, wind patterns, and natural ventilation, affecting energy performance and occupant comfort [112].

2.5.2.7 Thermal Mass
The ability of building materials to absorb, store, and release heat over time, helping to stabilize indoor temperatures, reduce temperature fluctuations, and improve energy efficiency [112].

2.5.2.8 Window Opening
The design and placement of windows within a building envelope to optimize natural daylighting, views, ventilation, and solar heat gain, balancing energy efficiency and occupant comfort [135].

2.5.2.9 Double skin
A building facade consisting of two layers separated by an air gap, which provides additional thermal insulation, solar control, and acoustic performance, enhancing energy efficiency and indoor comfort [136].

2.5.2.10 Landscape
The design and management of outdoor spaces surrounding a building, including vegetation, hardscape elements, and water features, which can influence microclimate, solar exposure, and outdoor comfort [137].

2.5.2.11 Daylight
The use of natural sunlight to illuminate indoor spaces, reducing the need for artificial lighting, enhancing visual comfort, and improving energy efficiency [138].

2.5.2.12 Natural ventilation

2.5.2.12.1 Wind catcher

Architectural features that capture and channel prevailing winds into a building to provide passive cooling, ventilation, and air exchange, enhancing indoor air quality and comfort [139,140].

2.5.2.12.2 Courtyard and Atria

Open or semi-open spaces within a building or between buildings that facilitate natural ventilation, daylighting, and thermal comfort through cross ventilation and stack effect [139,140].

2.5.2.13 Night ventilation

The practice of using cooler outdoor air during nighttime hours to naturally ventilate and cool indoor spaces, reducing the need for mechanical cooling and improving energy efficiency [141].

2.5.2.14 Direct Evaporative Cooling

A passive cooling technique that uses the evaporation of water to lower air temperatures, typically achieved through wetted surfaces or evaporative cooling pads, enhancing indoor comfort in arid climates [142].

2.5.2.15 Indirect Evaporative Cooling

A variation of evaporative cooling that utilizes a heat exchanger to cool incoming air without adding moisture, improving energy efficiency and reducing humidity levels compared to direct evaporative cooling [143].

2.5.2.16 Ground Cooling

The use of underground or geothermal systems to extract heat from a building and dissipate it into the ground, leveraging the stable temperature of the earth for cooling purposes, enhancing energy efficiency and reducing HVAC loads [144].

2.5.3 Hybrid Strategies

Hybrid strategies in building design represent a sophisticated approach that seamlessly merges both active and passive methodologies to attain the highest levels of energy efficiency and sustainability. These strategies leverage the strengths of active systems, such as HVAC upgrades, alongside passive design features like superior insulation and strategic daylighting.

By integrating active and passive components, hybrid strategies aim to strike a delicate balance between energy consumption and conservation. Active systems, such as advanced HVAC technologies, offer dynamic control and adaptability to changing environmental conditions, ensuring optimal comfort for building occupants while minimizing energy wastage. On the other hand, passive design features capitalize on natural resources and architectural elements to passively regulate indoor temperatures and lighting levels. This may include utilizing effective insulation to reduce heat transfer, optimizing building orientation to harness solar gain, and incorporating daylighting strategies to minimize reliance on artificial lighting sources.

The synergy between active and passive approaches is the cornerstone of hybrid strategies, enabling buildings to achieve exceptional energy performance without compromising occupant comfort. By carefully integrating these elements, hybrid buildings can significantly reduce energy consumption, lower operational costs, and mitigate environmental impact, thus paving the way towards a more sustainable built environment [145,146].

2.5.4 Energy Sources

Figure 2-14 provides an overview of energy sources categorized into non-renewable and renewable categories. Non-renewable energy sources include fossil fuels (coal, oil, natural gas) and nuclear power, which are finite and contribute to environmental pollution. On the other hand, renewable energy sources are naturally replenished and environmentally sustainable. These include wind power systems, hydropower energy, geothermal energy, biomass, fuel cell, and hydrogen, as well as various solar power systems. Solar power systems are further subdivided into crystalline photovoltaic (PV) modules (mono-crystalline, poly-crystalline), amorphous PV modules, and solar thermal systems, each offering unique advantages for harnessing solar energy.

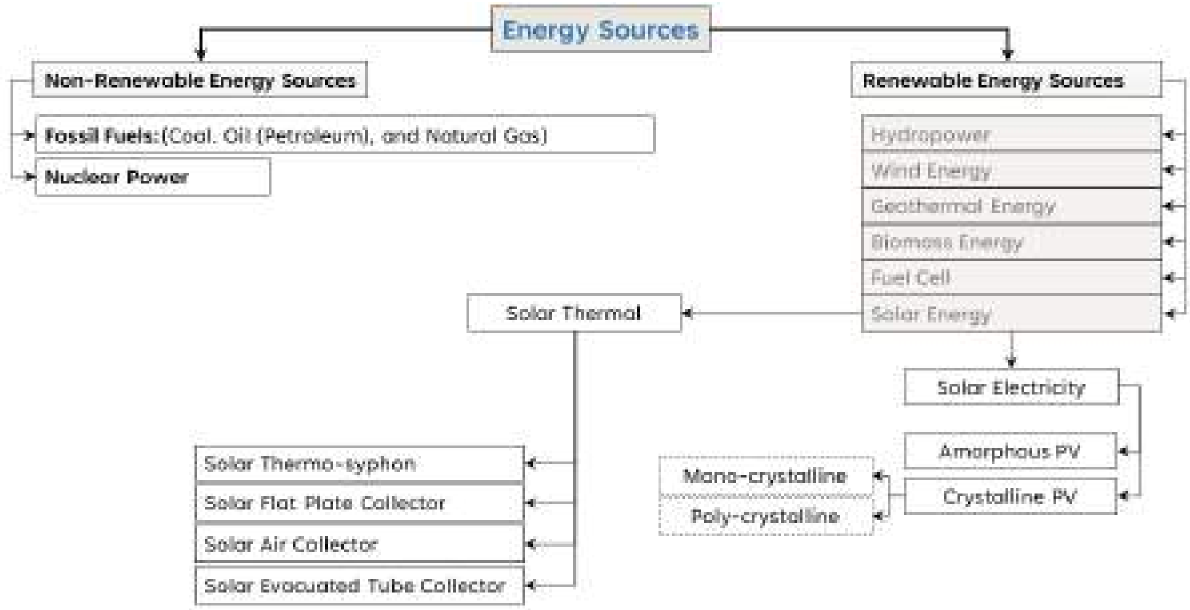


Figure 2-14 Overview of energy sources and technologies [83]

2.5.4.1 Non-Renewable Energy Sources

Non-renewable energy sources refer to traditional fuels such as fossil fuels (coal, oil, natural gas) and nuclear power. These sources are finite in supply and are extracted from the Earth's crust. While they have been integral to meeting global energy demands, they also pose significant environmental challenges. The combustion of fossil fuels releases greenhouse gases and other pollutants, contributing to climate change, air pollution, and environmental degradation [147-149].

2.5.4.1.1 Fossil Fuels

- *Coal:* A combustible black or brownish-black sedimentary rock formed from fossilized plant matter, used primarily for electricity generation and industrial processes.
- *Oil (Petroleum):* A naturally occurring liquid found beneath the Earth's surface, used as a source of energy in transportation, heating, and electricity generation.
- *Natural Gas:* A flammable gas consisting mainly of methane and other hydrocarbons, used for heating, cooking, electricity generation, and as a fuel for vehicles.

2.5.4.1.2 Nuclear Power

Nuclear power relies on nuclear reactions, typically the fission of uranium or plutonium isotopes, to generate heat, which is then converted into electricity. While nuclear power does not produce greenhouse gas emissions during operation, it generates radioactive waste and poses safety and environmental risks.

2.5.4.2 Renewable Energy Sources

Renewable energy sources encompass sustainable alternatives that are naturally replenished over time. These sources include solar, wind, hydroelectric, geothermal, and biomass energy. Unlike non-renewable sources, renewable energy options offer cleaner and more environmentally friendly solutions to meet energy needs. Solar power systems harness sunlight through photovoltaic (PV) modules or solar thermal systems, while wind power systems utilize wind turbines to generate electricity. Hydropower energy converts the kinetic energy of flowing water into electrical power, while geothermal energy taps into the Earth's heat stored beneath its surface. Biomass energy utilizes organic materials such as wood, agricultural residues, and municipal waste for heat and electricity generation. Additionally, fuel cells and hydrogen technologies represent innovative approaches to energy production and storage, offering promising solutions for a sustainable energy future [150-152].

2.5.4.2.1 Solar Power Systems

- *Crystalline PV Modules:* These modules use silicon-based solar cells to convert sunlight into electricity efficiently. They are commonly used in residential, commercial, and utility-scale solar installations.
- *Amorphous PV Modules:* Also known as thin-film solar panels, these modules utilize non-crystalline silicon to produce flexible and lightweight solar panels suitable for various applications, including building-integrated photovoltaics.

2.5.4.2.2 Solar Thermal Systems

- *Solar Thermosyphon:* A passive solar water heating system that uses natural convection to circulate water between solar collectors and a storage tank.
- *Solar Flat Plate Collector:* A common type of solar thermal collector consisting of a flat, rectangular absorber plate to capture solar energy for heating water or air.
- *Solar Air Collector:* Utilizes solar energy to heat air for space heating or ventilation applications.
- *Solar Evacuated Tube Collector:* Consists of a series of evacuated glass tubes that collect and transfer solar energy for heating water or air.

2.5.4.2.3 Wind Power Systems

Wind turbines convert kinetic energy from the wind into mechanical power, which is then converted into electricity. They are typically installed in wind farms on land or offshore.

2.5.4.2.4 Hydropower Energy

Hydropower utilizes the gravitational force of flowing or falling water to generate electricity. It includes conventional hydroelectric dams, run-of-river hydroelectric systems, and pumped-storage hydroelectricity.

2.5.4.2.5 Geothermal Energy

Geothermal energy harnesses heat from beneath the Earth's surface for electricity generation and direct heating and cooling applications. It involves tapping into hot water or steam reservoirs deep underground.

2.5.4.2.6 Biomass

Biomass energy is derived from organic materials such as wood, agricultural residues, and organic waste. It can be converted into heat, electricity, or biofuels through processes like combustion, gasification, and anaerobic digestion.

2.5.4.2.7 Fuel Cell and Hydrogen

Fuel cells use electrochemical reactions to convert hydrogen and oxygen into electricity and heat. Hydrogen can be produced from renewable sources through electrolysis or steam methane reforming and has the potential to serve as a clean and versatile energy carrier.

2.6 Building Envelope Components

The building envelope, often referred to as the building shell or building enclosure, is a critical component of any structure, serving as its first line of defense against external elements and influences. Comprising walls, fenestration (windows and doors), thermal insulation, thermal mass, and various other components, the building envelope plays a pivotal role in maintaining structural integrity, energy efficiency, and indoor comfort. By effectively separating the indoor environment from the outdoor surroundings, the building envelope regulates temperature, controls moisture infiltration, provides natural lighting and ventilation, and contributes to the overall sustainability and performance of the building. Understanding the key components of the building envelope and their functions is essential for designing and constructing resilient, energy-efficient, and comfortable buildings.

2.6.1 Walls

Walls form an integral part of the building envelope, providing structural support and delineating the boundary between the interior and exterior spaces. They serve as barriers against weather elements, noise, and intruders while also contributing to thermal insulation and aesthetic appeal. Common wall materials include concrete, brick, wood, steel, and various composite materials, each offering unique properties in terms of strength, durability, and thermal performance. The design and construction of walls are influenced by factors such as building codes, climate conditions, architectural style, and desired functionality. Proper insulation and moisture management are essential considerations to enhance energy efficiency and prevent issues such as condensation and mold growth. Additionally, advancements in building technology have led to the development of innovative wall systems, such as insulated concrete forms (ICFs), structural insulated panels (SIPs), and green walls, which offer enhanced thermal performance, sustainability, and design flexibility. Understanding the role of walls in the building envelope is crucial for optimizing building performance and occupant comfort [112].

2.6.1.1 Passive solar walls

Passive solar walls efficiently harness and distribute solar energy within buildings, primarily in cold climates. These walls feature a 12-inch-thick concrete layer on the southern facade, absorbing solar radiation. Glazing acts as an outer layer, creating a greenhouse effect. Numerous advancements have emerged from classical Trombe wall designs, including composite Trombe-Michell walls. For cold climatic conditions, innovative designs like steel-backed panels with polystyrene insulation have enhanced operational efficiency. Comparative studies have analyzed different solar wall configurations, with preference for convection-based designs like composite solar walls or insulated Trombe walls in regions with shorter heating seasons. However, regions with longer heating seasons may benefit from conduction-based designs like Trombe walls or unventilated solar walls. Strategies like solar shields help prevent overheating in the summer [153-157]. Innovative approaches include PV-integrated Trombe walls, phase change material (PCM) based Trombe walls, and fluidized Trombe wall systems (Figure 2-15 (a)). The Transwall (Figure 2-15 (b)), a transparent modular wall, provides both heating and illumination, utilizing water enclosed between parallel glass panes [158-161].

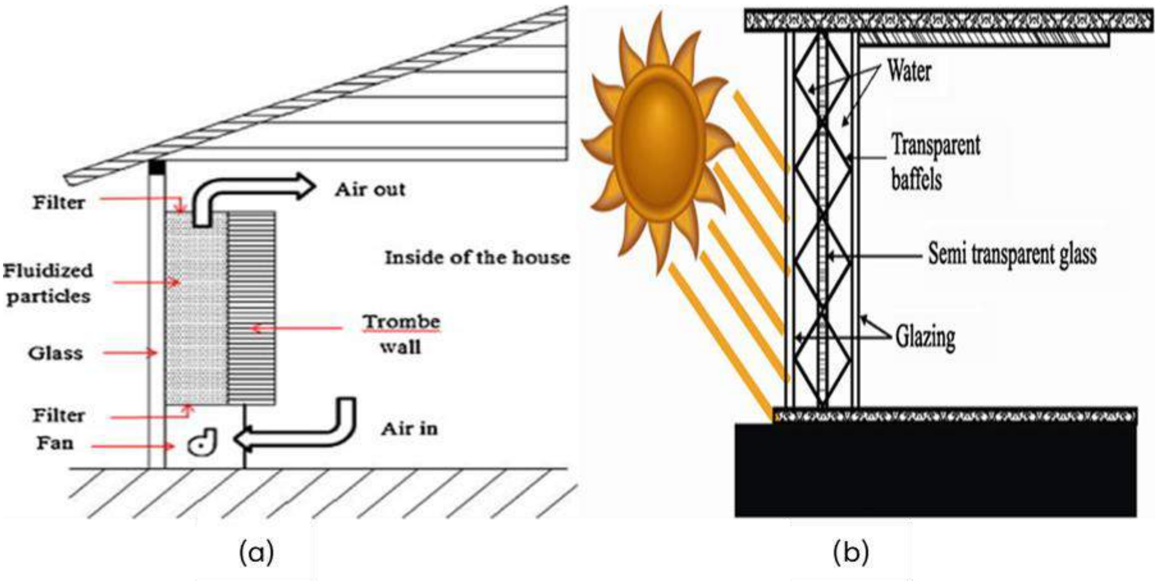


Figure 2-15 Passive solar walls: (a)- Visualization of fluidized Trombe wall system Components [160]; (b)- Transwall System: a cross-sectional perspective [162]

2.6.1.2 Lightweight concrete (LWC) walls

Lightweight concrete (LWC) refers to any concrete produced with a density of less than 2000 kg/m3, offer versatility in construction. Structural LWC ranges between 1600 and 2000 kg/m^3, while for thermal insulation, it's under 1450 kg/m^3. Incorporating lightweight aggregates, such as polystyrene beads, improves thermal resistance [163]. Autoclaved aerated concrete (AAC), a type of LWC, provides superior thermal resistance and is gaining popularity as a wall material, particularly in developing countries. AAC has a density of 600-800 kg/m^3 [164]. These walls are advantageous in regions where concrete construction is common and insulation practices are limited, offering faster construction with less skilled labor.

Recently, Engineers used CLC blocks over conventional clay bricks for building walls due to their lower density. CLC blocks lighten the load on buildings, being lighter and requiring less cement and aggregate. They also offer benefits like thermal insulation and sound suppression, saving time during installation. Generally, CLC blocks are larger in size compared to clay bricks, as illustrated in Figure 2-16 for a visual comparison [165].

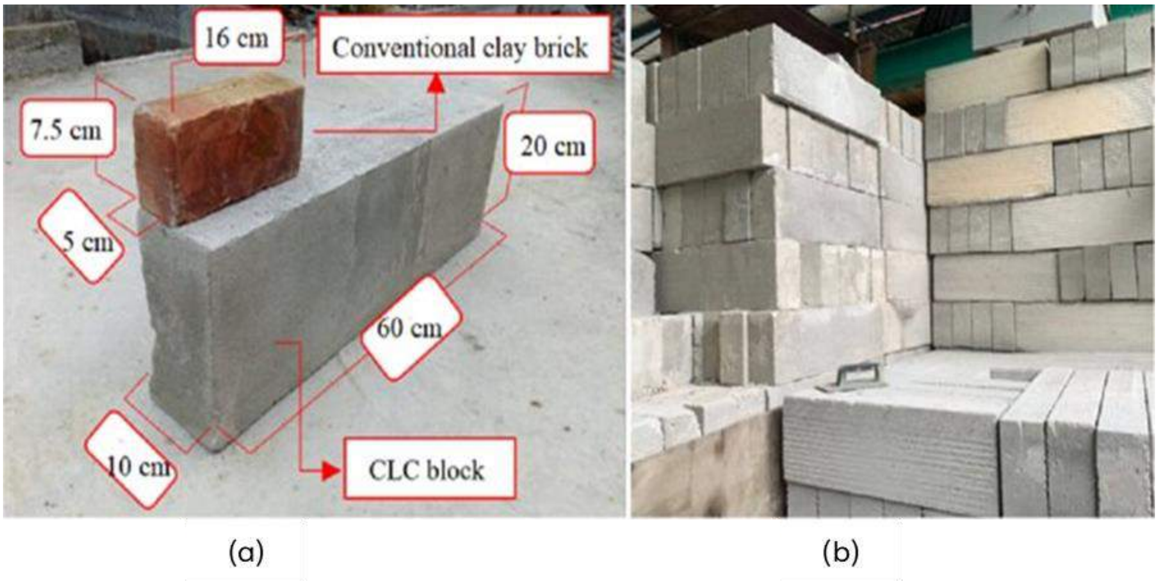


Figure 2-16 Comparison of Cellular Lightweight Concrete (CLC) blocks with conventional clay brick: (a)- Size comparison; (b)- Set of hardened CLC [165]

2.6.1.3 Ventilated or double skin walls

Ventilated or double-skin walls refer to a construction method where two layers of walls are built with an air gap or cavity between them. This design allows for improved thermal performance, moisture control, and sound insulation. The outer layer typically acts as a weather barrier, while the inner layer provides structural support and insulation. The air gap between the two layers helps to reduce heat transfer and allows for natural ventilation, enhancing the overall energy efficiency and comfort of the building.

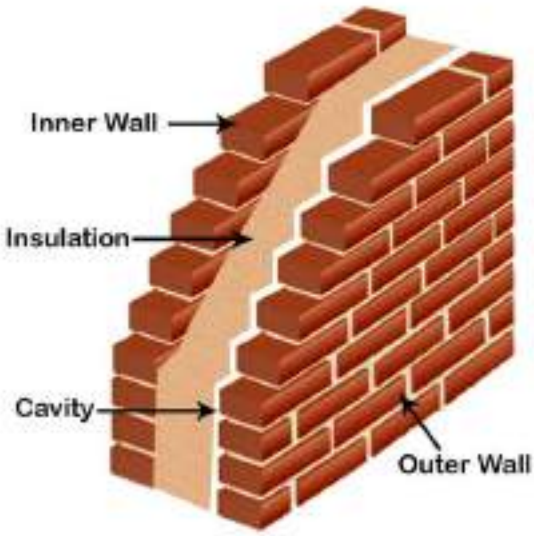


Figure 2-17 Schematic representation of ventilated or double-skin walls [166]

Research by Barbosa and Ip [167] highlights the potential of double skin facades for naturally ventilated buildings, emphasizing their role in sustainable architecture. Tao et al. [168] examine the ventilation performance of such facades, shedding light on their effectiveness in regulating indoor air quality and temperature. Similarly, studies by Dama et al. [169] provide insights into the modeling and experimental aspects of naturally ventilated double-skin facades, further supporting their integration into contemporary building designs.

2.6.1.4 Walls with latent heat storage

Walls with latent heat storage refer to wall structures designed to store and release heat through the use of phase change materials (PCMs). These materials absorb and release large amounts of heat when they change from one phase to another (e.g., solid to liquid or vice versa) at a specific temperature. In such walls, PCMs are integrated into the construction material or incorporated as a separate layer within the wall assembly. During periods of high temperatures, the PCM absorbs excess heat, causing it to change phase and store thermal energy. Conversely, during cooler periods, the PCM releases stored heat as it changes back to its original phase, thereby helping to maintain a more stable indoor temperature and reduce the need for mechanical heating and cooling systems.

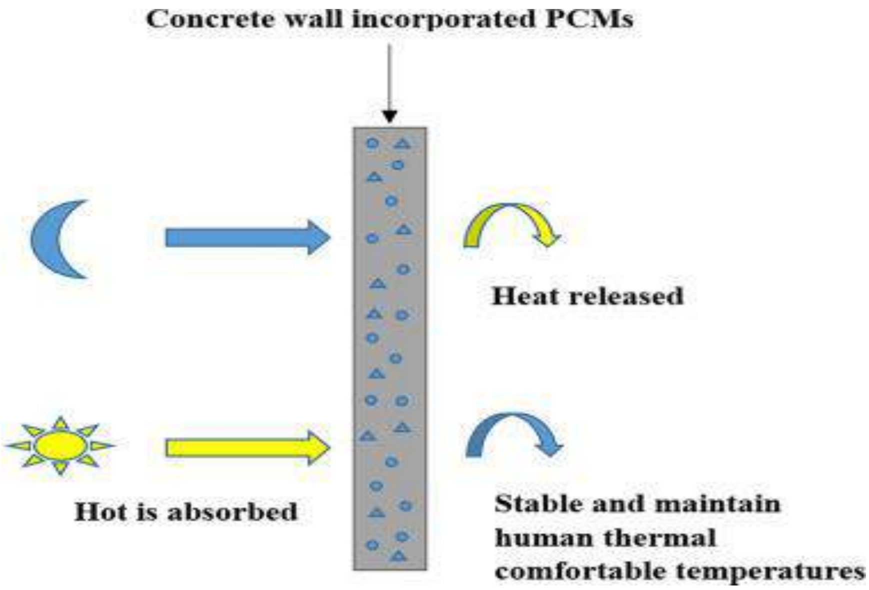


Figure 2-18 Functioning of concrete walls with incorporated Phase Change Materials (PCMs) for latent heat storage [170]

Figure 2-18 illustrates the working principle of concrete walls integrated with Phase Change Materials (PCMs) for latent heat storage. PCMs embedded within the concrete structure absorb and release thermal energy during phase transitions, typically between solid and liquid states. During high temperatures, the PCM absorbs heat and changes phase, storing energy. Conversely, during cooler periods, the PCM releases stored heat as it reverts to its original phase, aiding in temperature regulation within the building.

Walls with latent heat storage, integrating phase change materials (PCMs), offer innovative solutions for energy conservation in building applications. Khudhair and Farid [171] provide a comprehensive review of energy conservation techniques utilizing thermal storage by latent heat, particularly focusing on the use of PCMs in building applications. Arıcı et al. [172] contribute to this field with an optimization study aimed at maximizing the activation of latent heat through the integration of PCM into external building walls, emphasizing the potential for enhanced energy efficiency and thermal regulation in construction practices.

2.6.2 Fenestration (windows and doors)

Fenestration refers to the design, placement, and arrangement of windows, doors, and other openings in a building's envelope. Windows and doors play pivotal roles in regulating natural light, ventilation, and thermal comfort within indoor spaces, while also influencing the building's aesthetic appeal and energy performance [173].

Windows come in various types, including casement, double-hung, awning, fixed, and sliding, each offering unique benefits in terms of functionality, ventilation, and style. Modern window technologies often feature double or triple glazing, low-emissivity coatings, and gas fills to improve thermal efficiency and reduce heat transfer. Additionally, considerations such as window orientation, size, and shading devices impact solar heat gain, daylighting, and glare control.

Similarly, doors serve as access points between indoor and outdoor areas, providing security, weather resistance, and architectural character. Common door materials include wood, steel, fiberglass, and aluminum, with options for insulation, weatherstripping, and energy-efficient glazing.

Effective fenestration design integrates passive strategies such as daylighting, natural ventilation, and solar heat gain control to enhance indoor environmental quality and reduce reliance on mechanical systems. Understanding fenestration principles and selecting appropriate window and door solutions are essential for optimizing energy performance, occupant comfort, and building functionality [173].

2.6.2.1 Types of glazing materials and technologies

Various glazing materials and technologies are pivotal in modern building construction, enhancing energy efficiency, visual comfort, and overall performance. Researchers have extensively reviewed these advancements, spanning from conventional to smart innovations aimed at improving indoor environments [174-176].

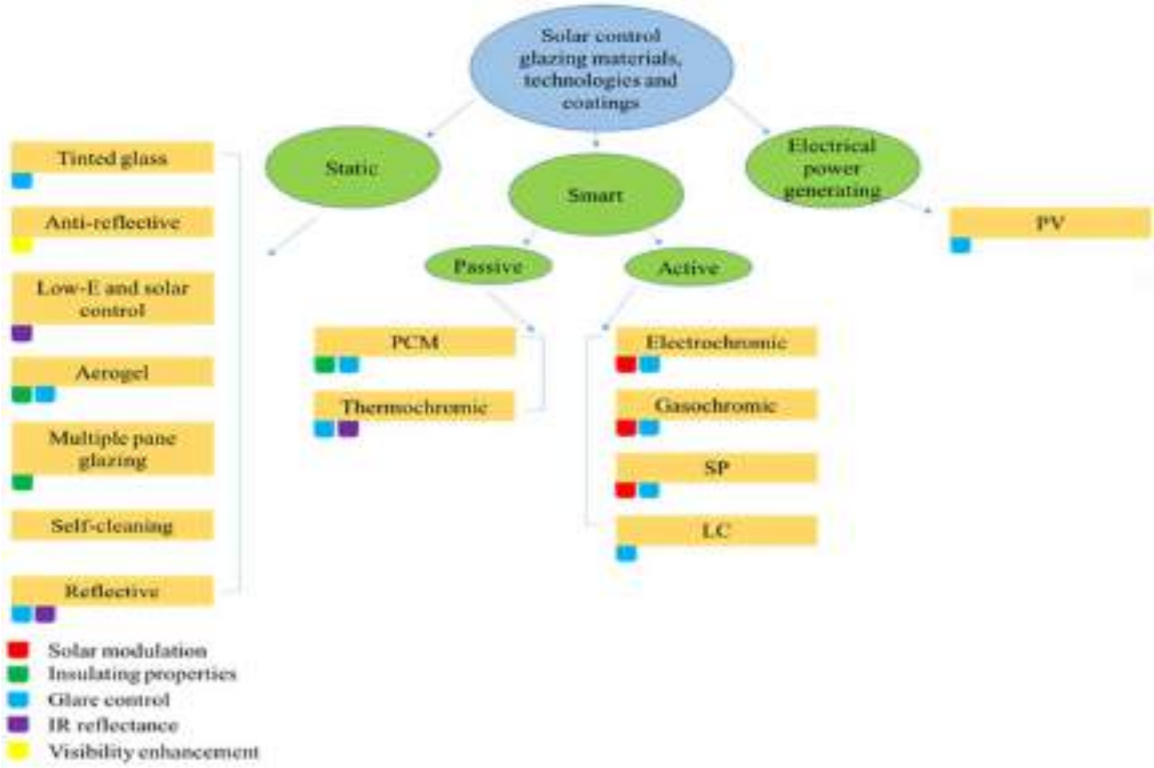


Figure 2-19 Categorization of glazing materials and technologies [174]

These studies emphasize the dynamic nature of glazing solutions and their vital role in shaping sustainable built environments. These materials and technologies include:

2.6.2.1.1 Low-E (Low-Emissivity) Glass

Low-E glass, discussed extensively by Jelle, Kalnæs, and Gao [177], stands out as a key innovation in glazing materials. This glass is coated with a thin metallic layer that serves a dual purpose. During the winter months, it reflects heat back into the room, thus reducing heating costs while still allowing natural sunlight to penetrate, enhancing comfort and reducing reliance on artificial lighting. In the summer, Low-E glass reflects solar radiation, effectively reducing cooling needs and maintaining a comfortable indoor environment. This technology represents a significant advancement in energy-efficient building design and contributes to overall sustainability efforts within the construction industry.

2.6.2.1.2 Insulated Glass Units (IGUs)

Insulated Glass Units (IGUs), as detailed by Respondek [178], represent a significant advancement in glazing technology. These units typically comprise two or more glass panes separated by an insulating spacer filled with air or gas, such as argon or krypton. This design effectively improves thermal insulation by creating a barrier against heat transfer, thereby reducing energy consumption for heating and cooling purposes. Additionally, IGUs help minimize condensation on interior glass surfaces, contributing to improved indoor air quality and comfort. Furthermore, the presence of multiple glass layers and the insulating spacer enhances soundproofing properties, creating a quieter indoor environment. IGUs are widely utilized in modern building construction to optimize energy efficiency and enhance occupant comfort.

2.6.2.1.3 Tinted Glass

Tinted Glass offers a practical solution for controlling solar heat gain and glare in buildings. This type of glass is treated with a film or coating that reduces the transmission of solar radiation and glare into indoor spaces. By limiting the amount of sunlight that enters a building, tinted glass helps regulate indoor temperatures, reducing the need for excessive cooling during hot weather. Additionally, it protects against UV radiation, preventing damage to furnishings and interior finishes [179].

2.6.2.1.4 Reflective Glass

Reflective Glass incorporates a metallic coating designed to reflect solar radiation, effectively reducing heat gain and glare within buildings. Its application is particularly beneficial in hot climates, where it enhances energy efficiency and improves occupant comfort by minimizing the need for excessive cooling. The reflective properties of this glass type contribute to maintaining comfortable indoor temperatures while also mitigating the impact of intense sunlight [180].

2.6.2.1.5 Smart Glass

Smart Glass, also known as switchable glass, possesses the unique ability to alter its transparency or opacity based on external stimuli like light intensity or temperature. This innovative technology provides dynamic control over factors such as privacy, daylighting, and solar heat gain, offering versatility and adaptability in various building applications [181].

2.6.2.1.6 Self-Cleaning Glass

Self-cleaning glass incorporates a hydrophilic coating that effectively disintegrates organic dirt, enabling water to disperse evenly across its surface. This feature facilitates the removal of dirt particles through rainfall or simple rinsing with water, maintaining the glass's cleanliness with minimal effort [182].

2.6.2.1.7 Vacuum Insulated Glass (VIG)

VIG consists of two glass panes separated by a vacuum layer, which minimizes heat transfer through conduction and convection. This technology offers excellent thermal insulation in a slim profile [183].

2.6.2.1.8 Aerogel Glazing

Aerogel Glazing, a cutting-edge technology in building applications, harnesses the remarkable properties of aerogel. This material, known for its highly porous structure and exceptionally low thermal conductivity, serves as an effective insulating layer within glazing systems. By incorporating aerogel into the design, these glazing assemblies achieve superior thermal performance compared to traditional alternatives. Despite its insulating properties, aerogel allows ample daylight transmission, ensuring well-lit and energy-efficient indoor spaces [184].

2.6.2.1.9 Electrochromic Glass

Electrochromic glass revolutionizes building design by providing dynamic control over solar heat gain and glare. With the application of an electric current, this innovative glass can adjust its tint or opacity, optimizing visual comfort and energy efficiency within indoor spaces. By regulating the amount of sunlight entering the building, electrochromic glass reduces the need for heating and cooling, thereby lowering energy consumption and enhancing sustainability [185].

2.6.2.1.10 Photovoltaic (PV) Glass

PV glass represents a groundbreaking advancement in building technology, merging energy generation with structural functionality. By integrating solar cells directly into the glazing system, PV glass enables buildings to harness solar energy and convert it into electricity while also serving as a fundamental component of the building envelope. This innovative approach not only facilitates sustainable energy production but also enhances daylighting and shading functionalities within the built environment [186].

These glazing materials and technologies offer a range of options for architects and designers to optimize building performance, energy efficiency, and occupant comfort in various climates and contexts.

2.6.2.2 Frames

The efficacy of modern fenestrations heavily relies on the design and composition of their edge components, particularly the frame and spacer, to mitigate thermal bridging and infiltration losses. Robinson and Hutchins [187]. elucidated the impact of different combinations of frames and spacers on the U-value, a measure of thermal transmittance, across various window types, underscoring the importance of these elements in enhancing energy efficiency. Moreover, it's noted that such edge effects are more pronounced in smaller-sized windows, magnifying the significance of optimizing frame and spacer configurations for overall performance.

In a comprehensive review by Gustavsen et al. [188] the imperative of low-conductance frames is reiterated, emphasizing the pivotal role of frame materials and design in minimizing heat transfer. This underscores the ongoing pursuit within the industry to develop and implement frames with superior insulating properties, aligning with the overarching goal of advancing energy-efficient building practices.

2.6.3 Roofs

Roofs serve as vital protective barriers, shielding buildings from weather elements like rain, snow, wind, and sunlight, while significantly impacting energy efficiency and sustainability. They come in various types, including pitched and flat roofs, each tailored to specific architectural designs and climate conditions.

Materials for roof construction vary widely, from traditional options like asphalt shingles to innovative ones such as cool roofs, which reflect sunlight and reduce heat absorption, thereby lowering cooling loads and energy consumption.

Roofs also enhance energy efficiency and sustainability through insulation, ventilation, and integration of renewable energy systems like solar panels and green roofs. Proper insulation prevents heat loss or gain, while ventilation systems promote air circulation and moisture control, reducing energy costs and the risk of damage.

Furthermore, roofs provide an ideal platform for the installation of solar photovoltaic (PV) panels, solar thermal collectors, and green roof systems, harnessing sunlight to generate electricity, heat water, and provide additional insulation and cooling benefits, further enhancing building sustainability and resilience.

2.6.3.1 Types of roofs

Roofs can be classified into different categories based on the type of construction. The following sections present some of the commonly used roofing structures along with recent developments.

2.6.3.1.1 Masonry roofs

Masonry roofs, characterized by their use of durable materials like bricks, stones, or concrete blocks, offer longevity, strength, and thermal mass properties that contribute to energy efficiency and thermal comfort. While less common in modern residential construction, they are still valued in historic, industrial, and commercial buildings for their robustness and aesthetic appeal. However, they require strong structural support due to their weight and meticulous waterproofing to prevent moisture-related issues.

Recent advancements in masonry construction techniques have led to innovations in roofing systems that combine traditional durability with modern design and performance standards, ensuring that masonry roofs remain a viable option for specific applications where their unique characteristics are desired [189].

2.6.3.1.2 Lightweight roofs

Lightweight roofs are roofing systems designed to minimize structural load while providing adequate protection and insulation. These roofs are typically constructed using lightweight materials such as metal, plastic, or composite materials. One common type of lightweight roof is metal roofing, which can be made from materials like aluminum, steel, or copper. Metal roofs are lightweight, durable, and resistant to fire, insects, and rot. Another popular option is synthetic roofing materials, such as plastic or composite shingles, which mimic the appearance of traditional roofing materials like wood or slate but are much lighter in weight. Lightweight roofs offer several advantages, including easier installation, reduced structural requirements, and improved energy efficiency. They are suitable for a wide range of building types, including residential, commercial, and industrial structures. However, lightweight roofs may have limitations in terms of durability and longevity compared to traditional roofing materials. Therefore, proper maintenance and periodic inspections are essential to ensure the continued performance and integrity of lightweight roofing systems [190].

2.6.3.1.3 Ventilated and micro-ventilated roofs

Ventilated and micro-ventilated roofs are roofing systems designed to improve energy efficiency, thermal comfort, and moisture control in buildings by promoting airflow within the roof assembly. In a ventilated roof system, a gap or airspace is created between the roof deck and the roofing material, allowing for natural convection to occur. This airflow helps to remove excess heat and moisture from the roof space, reducing the risk of condensation, mold growth, and structural damage. Micro-ventilated roofs take this concept further by incorporating smaller ventilation channels or openings within the roofing material itself, allowing for more controlled airflow while still providing insulation and weather protection. These innovative roof designs help to regulate indoor temperatures, reduce cooling loads in hot climates, and improve overall building performance. Additionally, ventilated and micro-ventilated roofs can extend the lifespan of roofing materials by minimizing moisture-related issues and reducing thermal stress. Overall, these roofing systems offer a sustainable and cost-effective solution for enhancing comfort and durability in buildings [191].

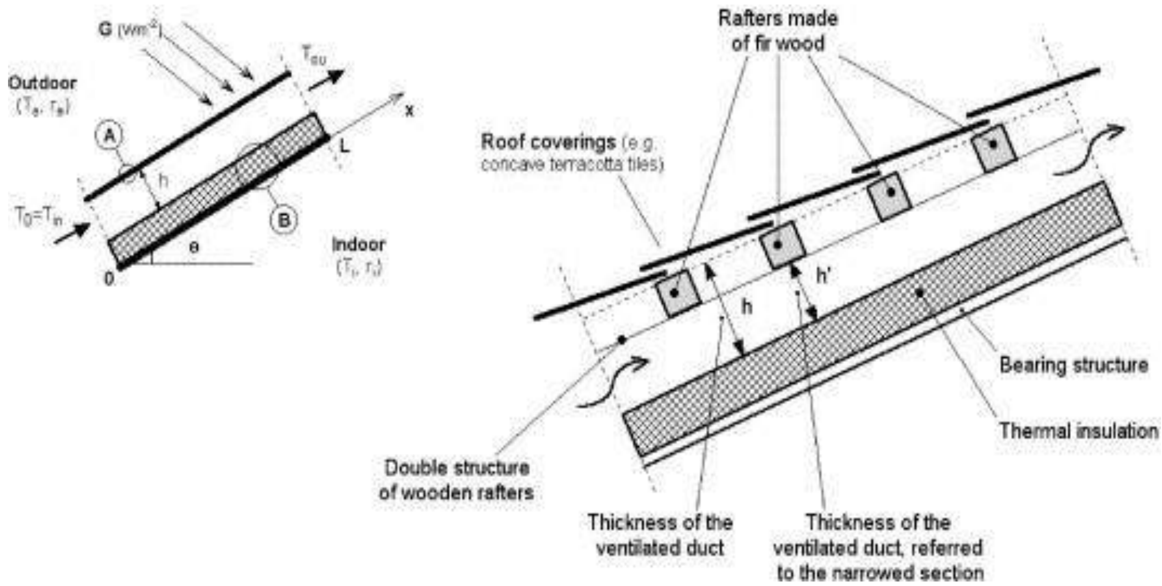


Figure 2-20 Efficient Airflow dynamics in ventilated roofing systems [192]

Figure 2-20 delineates the architectural design of ventilated and micro-ventilated roofs. It emphasizes the strategic layering of roofing materials to create an air cavity that allows for continuous airflow. This design is instrumental in reducing heat accumulation and moisture retention, thereby improving the thermal efficiency and durability of the roofing structure. Such systems are pivotal in achieving optimal indoor climate control and energy savings.

2.6.3.1.4 Vaulted and domed roofs

Vaulted and domed roofs are architectural elements known for their elegance, spaciousness, and structural strength. Vaulted roofs feature arched or curved shapes, forming interconnected arches or vaults across interior spaces, while domed roofs are hemispherical or partially spherical. These roofs offer aesthetic appeal and functional advantages, such as creating grand, open interiors without the need for internal supports. They can optimize natural lighting and ventilation, reducing energy consumption. However, constructing curved structures requires specialized expertise and may involve higher costs and maintenance needs. Despite challenges, vaulted and domed roofs remain popular for their iconic beauty and cultural significance in various architectural contexts [193].

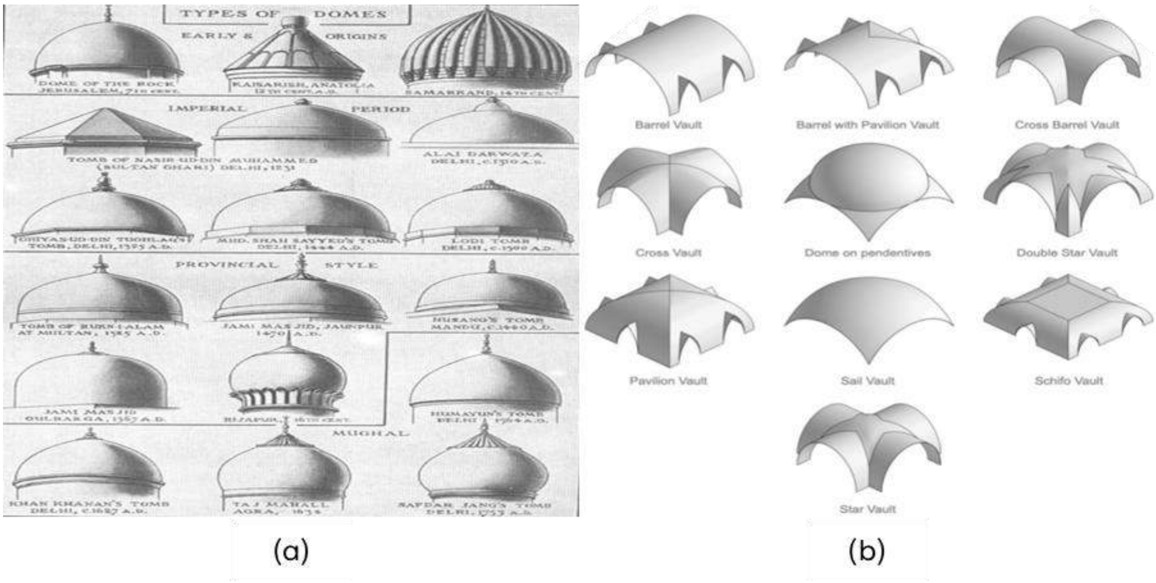


Figure 2-21 Sketches of domed and vaulted roof designs: (a)- domed roofs [194]; (b)- vaulted roofs [195]

Figure 2-21 provides sketches showcasing various designs of domed and vaulted roofs. These architectural illustrations offer insights into the diverse forms and structural configurations employed in constructing such roof types, highlighting their aesthetic appeal and functional characteristics.

2.6.3.1.5 Solar-reflective/cool roofs

Solar-reflective or cool roofs are roofing systems designed to reflect sunlight and absorb less heat compared to traditional roofs, thereby reducing heat transfer to the building below and lowering indoor temperatures. These roofs are typically coated with reflective materials that have high solar reflectance (the ability to reflect sunlight) and high thermal emittance (the ability to emit absorbed heat). By reflecting a larger portion of the sun's rays, cool roofs help minimize heat absorption, which can significantly reduce cooling loads and energy consumption in buildings, especially during hot summer months. Additionally, cool roofs contribute to mitigating the urban heat island effect, improving outdoor comfort, and extending the lifespan of roofing materials by reducing thermal stress. Despite their benefits, the effectiveness of cool roofs may vary depending on factors such as climate, building orientation, and roof color. However, with ongoing advancements in materials science and roof coating technologies, solar-reflective roofs continue to be a valuable strategy for enhancing energy efficiency, comfort, and sustainability in buildings while reducing environmental impact and operating costs [196].

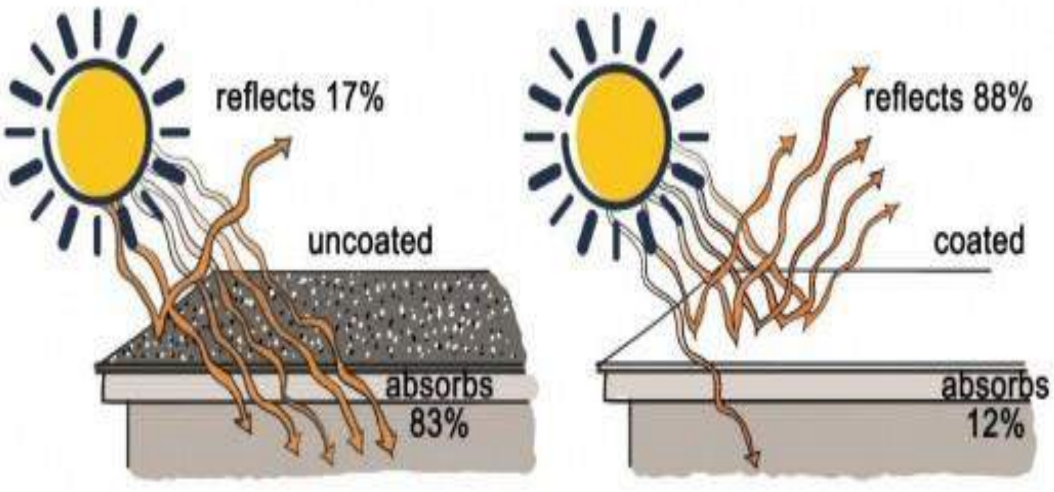


Figure 2-22 Comparison of uncoated and coated roofs for solar-reflective/cool roof applications [197]

Figure 2-22 presents a visual comparison between uncoated and coated roofs, illustrating the concept of solar-reflective or cool roofs. By contrasting the surface characteristics and appearance of both types of roofs.

2.6.3.1.6 Green roofs

Green roofs, also known as living roofs or eco-roofs, are innovative roofing systems that incorporate vegetation and landscaping on the roof surface. These roofs consist of multiple layers, including a waterproofing membrane, a root barrier, a drainage system, a growing medium, and vegetation. The vegetation can range from grasses and sedums to shrubs and even small trees, depending on the roof's structural capacity and intended use. Green roofs offer numerous benefits, including stormwater management by absorbing and filtering rainwater, reducing runoff, and alleviating pressure on urban drainage systems. They also provide insulation, reducing heat loss in winter and heat gain in summer, which can lead to energy savings and improved thermal comfort indoors. Additionally, green roofs help mitigate the urban heat island effect by absorbing solar radiation and releasing it through evapotranspiration, thereby lowering ambient temperatures in urban areas. Furthermore, these roofs contribute to biodiversity by providing habitats for birds, insects, and other wildlife, as well as improving air quality by filtering pollutants and capturing carbon dioxide. From an aesthetic perspective, green roofs enhance the visual appeal of buildings, create green spaces in urban environments, and promote a connection with nature for building occupants. Overall, green roofs represent a sustainable and environmentally friendly roofing solution that offers a range of ecological, social, and economic benefits for both buildings and cities [198,199]

Figure 2-23 Residential model demonstrating green roof integration [200]

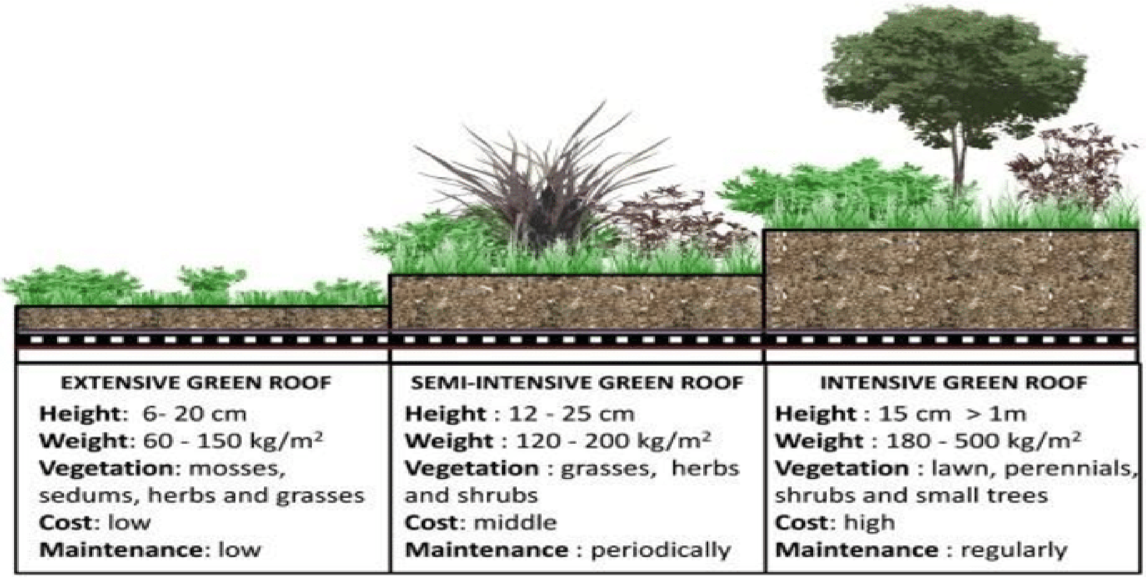


Figure 2-24 Types of green roofs [201]

Figure 2-23 illustrates a detailed model showcasing the application of green roofs in residential settings, highlighting their potential for enhancing aesthetics, improving insulation, and promoting environmental sustainability. In Figure 2-24, various types of green roofs are depicted, including extensive, intensive, and semi-intensive designs, each visually representing differences in vegetation coverage, substrate depth, and maintenance requirements. This comprehensive overview offers insight into the diverse options available for implementing green roof technology in urban and suburban environments.

2.6.3.1.7 Photovoltaic roofs

Photovoltaic (PV) roofs are roofing systems that integrate solar panels directly into the roof structure, allowing buildings to generate electricity from sunlight. These roofs consist of solar panels made up of photovoltaic cells, which convert sunlight into electrical energy through the photovoltaic effect. Photovoltaic roofs offer several advantages, including renewable energy generation, reduced dependence on fossil fuels, and lower electricity bills for building owners. Additionally, PV roofs contribute to sustainability by reducing greenhouse gas emissions and mitigating climate change. They also provide energy independence and resilience, particularly in remote or off-grid locations where access to traditional power sources may be limited. Moreover, photovoltaic roofs can enhance the architectural design of buildings, offering a sleek and modern aesthetic while simultaneously serving a functional purpose. However, challenges such as initial installation costs, efficiency limitations, and the need for proper maintenance and monitoring should be considered when implementing PV roofing systems. Despite these challenges, photovoltaic roofs represent a promising technology for promoting clean energy production and advancing sustainable building practices [202,203].

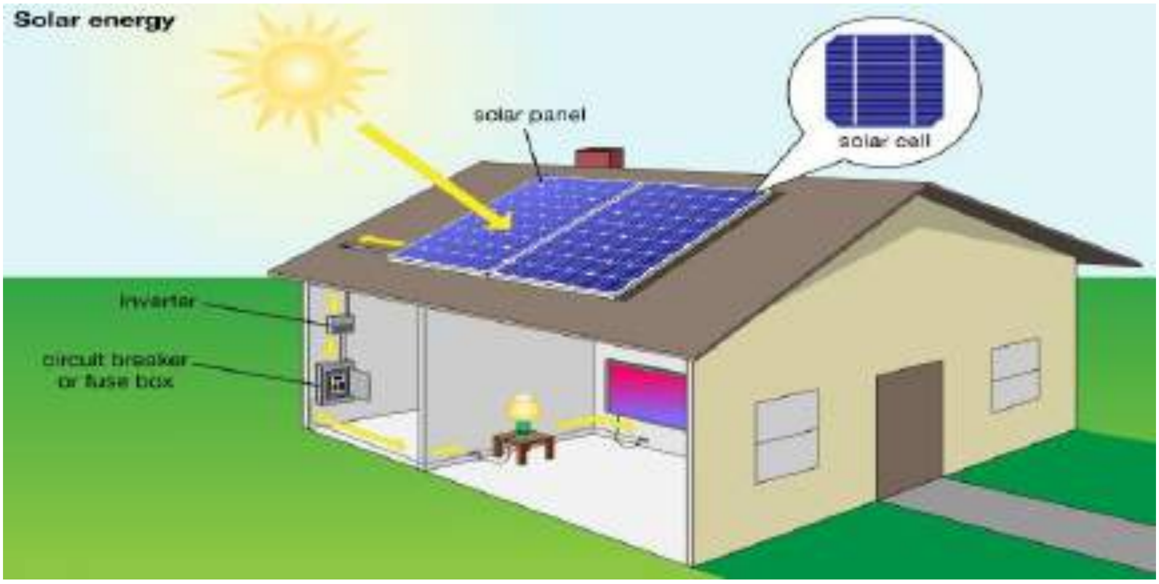


Figure 2-25 Residential solar power system [204]

Figure 2-25 illustrates a residential photovoltaic (PV) roofing system, which includes solar panels installed on the roof to capture solar energy. PV roofs are a sustainable energy solution that can reduce electricity bills and lower carbon footprints by harnessing renewable solar energy. They are an integral part of modern green building practices.

2.6.3.1.8 Thermal roof insulation systems

Thermal roof insulation systems play a crucial role in modern building design, particularly due to the significant amount of thermal energy loss that occurs through roofs. Research indicates that up to 60% of thermal energy leakage in buildings can be attributed to inadequately insulated roofs, underscoring the importance of effective insulation [112]. By implementing proper roof insulation, buildings can significantly reduce both heating and cooling loads, leading to substantial energy savings and improved overall energy efficiency. Sadineni et al. [112] emphasize the potential of passive building energy-saving strategies, with a particular focus on building envelope components, including roof insulation.

2.6.3.1.9 Evaporative roof cooling

Evaporative roof cooling is a method used to lower temperatures within a building by harnessing the natural cooling effect of water evaporation. This technique involves the installation of evaporative cooling systems on the roof, which utilize water to cool down the surrounding air. As water evaporates, it absorbs heat from the air, resulting in a drop in temperature. Evaporative cooling is particularly effective in hot and dry climates, where the air has low humidity levels. By incorporating evaporative roof cooling systems, buildings can achieve significant reductions in indoor temperatures, providing occupants with greater comfort while also reducing the need for mechanical cooling systems. This approach offers an energy-efficient alternative to traditional air conditioning systems, contributing to overall energy savings and environmental sustainability. Ongoing research and advancements in evaporative cooling technology continue to enhance its effectiveness and applicability in diverse building environments, further promoting its adoption as a viable cooling solution [205].

2.6.4 Thermal insulation, thermal mass and phase change materials

Thermal insulation, thermal mass, and phase change materials (PCMs) are essential components of the building envelope that contribute to energy efficiency, indoor comfort, and climate resilience.

2.6.4.1 Thermal insulation

Thermal insulation plays a crucial role in building design and energy efficiency by slowing down the transfer of heat through a structure's envelope. By effectively reducing heat flow through conduction, convection, and radiation, thermal insulation helps maintain comfortable indoor temperatures and minimizes the need for excessive heating or cooling. This not only enhances occupant comfort but also leads to significant energy savings and reduces the size requirements of HVAC systems. Recent advancements in insulation materials, such as aerogels and phase-change materials, offer even greater performance capabilities, while sustainable strategies like green roofs and cool roofs further contribute to energy conservation and environmental sustainability. Overall, prioritizing thermal insulation in building design and construction is a cost-effective and environmentally responsible approach to achieving energy efficiency and promoting sustainable living [112,206].

2.6.4.1.1 Selection of insulation

The selection of insulation materials for buildings is a crucial decision that impacts energy efficiency, occupant comfort, and environmental sustainability. Key considerations include thermal performance, moisture resistance, environmental impact, cost-effectiveness, and ease of installation. Optimal insulation choices offer high thermal resistance, resist moisture infiltration, minimize environmental impact, provide cost savings over time, and are easy to install. By prioritizing these factors and selecting insulation materials accordingly, buildings can achieve improved energy efficiency, reduced operational costs, and enhanced sustainability [207].

2.6.4.1.2 Types of insulation

The thermal insulation available for buildings comes in various physical forms, each offering unique advantages and applications:

- *Mineral Fiber Blankets:* Available in batts and rolls, mineral fiber blankets are made from materials such as fiberglass and rock wool. They provide effective thermal insulation and are commonly used in residential and commercial buildings.
- *Loose Fill Insulation:* This type of insulation can be blown into cavities, offering flexibility in installation. Materials used include fiberglass and rock wool, providing excellent thermal resistance.
- *Poured-In or Mixed Insulation:* These insulation materials, such as cellulose, perlite, and vermiculite, can be poured into cavities or mixed with concrete during construction. They offer good thermal properties and are suitable for various building applications.

- *Rigid Boards:* Rigid insulation boards, made from materials like polystyrene, polyurethane, polyisocyanurate, and fiberglass, provide high thermal resistance and structural support. They are commonly used in walls, roofs, and floors.
- *Foamed or Sprayed-In Insulation:* This type of insulation, including polyurethane and polyisocyanurate, is applied as a foam or spray that expands to fill cavities and gaps. It offers excellent thermal performance and can conform to irregular shapes.
- *Boards or Blocks:* Insulation materials such as perlite and vermiculite are available in board or block form, offering versatility in installation and effective thermal insulation.
- *Insulated Concrete Blocks and Forms:* These specialized building blocks and forms incorporate insulation within their structure, providing both structural support and thermal resistance.
- *Reflective Materials:* Materials like aluminum foil and ceramic coatings reflect heat, reducing heat transfer through radiation. They are often used in conjunction with other insulation materials to enhance thermal performance.

These types of insulation can be classified into four categories based on their material type, as illustrated in Figure 2-26. providing a comprehensive range of options for achieving optimal thermal insulation in buildings [112,208].

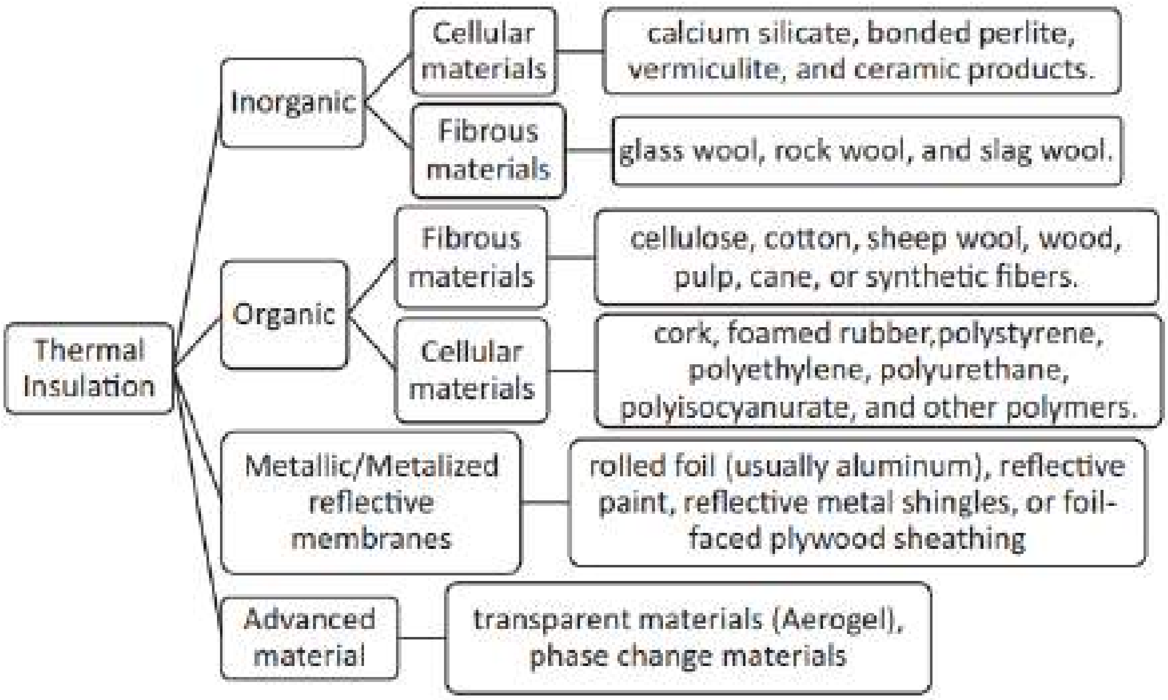


Figure 2-26 Various types of thermal insulation [112]

2.6.4.1.3 Vacuum insulation panels

Vacuum insulation panels (VIPs) are innovative insulation materials known for their exceptional thermal performance and slim profile. They consist of a core material enclosed within a gas-tight barrier envelope, with air evacuated to create a vacuum. VIPs offer high thermal resistance, allowing for thinner insulation layers compared to traditional materials. They are particularly useful in applications with limited space, such as building envelopes and appliances. Despite their high performance, VIPs are expensive and susceptible to damage. Overall, VIPs represent a significant advancement in insulation technology, providing unmatched thermal efficiency in a lightweight and compact form [209].

2.6.4.1.4 Structurally insulated panels (SIPs)

Structurally Insulated Panels (SIPs) are composite building materials typically used for walls, floors, and roofs in residential and commercial construction. SIPs consist of an insulating foam core sandwiched between two structural facings, such as oriented strand board (OSB). These panels offer several advantages, including high thermal performance, rapid installation, and superior strength. SIPs are prefabricated off-site, resulting in reduced construction time and labor costs. Additionally, their airtight construction minimizes heat loss and air infiltration, enhancing energy efficiency and indoor comfort. Despite their many benefits, SIPs may have limitations related to transportation and customization. Overall, SIPs are a versatile and efficient building solution that continues to gain popularity in the construction industry [112].

2.6.4.2 Thermal mass

Thermal mass refers to the ability of a material to absorb, store, and release heat energy. In building construction, materials with high thermal mass, such as concrete, brick, stone, and water, can help moderate indoor temperatures by absorbing heat during periods of high solar radiation or internal heat gains and releasing it later when temperatures drop. This property helps to stabilize indoor temperatures, reducing the need for mechanical heating and cooling systems and enhancing occupant comfort. Additionally, thermal mass can contribute to energy efficiency and sustainability by reducing overall energy consumption and reliance on fossil fuels for heating and cooling purposes. Properly incorporating thermal mass into building design and construction can optimize thermal comfort and energy performance, making it an essential consideration in sustainable building practices [210,211].

2.6.4.3 Phase change materials

Phase change materials (PCMs) are substances capable of storing and releasing large amounts of energy as they change phase from solid to liquid or vice versa. This phase change occurs at a specific temperature known as the melting or freezing point. During the phase transition, PCMs absorb or release latent heat, which can be used to regulate temperatures in buildings effectively. Common PCM types include paraffin wax, fatty acids, salt hydrates, and organic compounds. In building applications, PCMs are often encapsulated or embedded in building materials such as plaster, gypsum board, or concrete to form thermal energy storage systems. These systems absorb excess heat during the day when temperatures are high and release it at night when temperatures drop, helping to maintain comfortable indoor conditions and reducing the need for mechanical heating and cooling. PCMs offer a promising solution for improving energy efficiency, thermal comfort, and sustainability in buildings, particularly in regions with large diurnal temperature variations. However, challenges such as PCM degradation, compatibility with building materials, and cost-effectiveness need to be addressed to realize their full potential in the construction industry [212,213].

In summary, the integration of thermal insulation, thermal mass, and phase change materials in the building envelope plays a pivotal role in enhancing energy efficiency, thermal comfort, and sustainability. By minimizing heat transfer, regulating temperature fluctuations, and leveraging latent heat storage, these components contribute to optimized building performance and reduced environmental impact.

2.6.5 Infiltration and airtightness

Infiltration and airtightness are critical considerations in building envelope design, influencing energy efficiency, indoor air quality, and occupant comfort.

2.6.5.1 Infiltration

Infiltration refers to the unintended leakage of air into or out of a building through cracks, gaps, or openings in the building envelope. It occurs naturally due to pressure differentials between the interior and exterior of the building, wind effects, and temperature differentials. Infiltration can lead to energy loss, moisture intrusion, and reduced indoor air quality. Common infiltration pathways include gaps around windows and doors, penetrations for utilities, and joints between building materials. Proper sealing of these openings using weatherstripping, caulking, or gaskets is essential to minimize infiltration and optimize energy performance [214-216].

2.6.5.2 Airtightness

Airtightness refers to the degree to which a building envelope prevents air leakage. An airtight building envelope helps maintain indoor thermal comfort, reduces heating and cooling loads, and improves HVAC system efficiency. Achieving airtightness requires careful attention to construction details, including sealing joints, seams, and penetrations with air barriers or tapes. Blower door tests are commonly used to measure a building's airtightness by quantifying air leakage rates under controlled conditions. The results inform remediation efforts and help identify areas requiring additional sealing or insulation to enhance airtightness [214,216].

Improving infiltration and airtightness in the building envelope involves a holistic approach that considers both design and construction phases. Design strategies such as minimizing building openings, optimizing building orientation, and selecting appropriate materials with low air permeability can mitigate infiltration. During construction, quality control measures such as proper installation of air barriers, thorough sealing of penetrations, and attention to detail in junctions and transitions are essential to achieving airtightness goals [217,218].

In summary, addressing infiltration and ensuring airtightness are integral to optimizing building envelope performance, energy efficiency, and indoor environmental quality. By minimizing air leakage, designers and builders can create healthier, more comfortable, and more sustainable indoor environments while reducing energy consumption and operating costs.

2.6.5.3 Factors affecting infiltration

Infiltration, the process by which outdoor air enters a building and indoor air exit, is influenced by various factors. These include pressure differentials caused by temperature variations between indoor and outdoor air (known as the stack effect), wind movement, and the operation of mechanical ventilation systems and exhaust fans. Additionally, climatic conditions, the building's surroundings, its age, and construction characteristics play roles in determining the rate of infiltration. During heating, air tends to infiltrate through lower leaks in the building envelope and exfiltrate through higher leaks, while the reverse occurs during cooling. The operation of mechanical equipment, ventilation systems, and vented combustion appliances can also affect infiltration by either increasing or decreasing interior building pressure. Overall, understanding and controlling these factors are crucial for maintaining indoor air quality, thermal comfort, and energy efficiency in buildings [216,217].

2.6.5.4 Pollutant infiltration

Pollutant infiltration into buildings can occur through various means of ventilation, including mechanical ventilation, natural ventilation through openings like windows, and infiltration through cracks and leaks in the building envelope. In mechanically ventilated buildings, the efficiency of filters plays a significant role in determining the extent of ambient particle penetration. In contrast, naturally ventilated buildings tend to have higher particle penetration due to the larger openings for air exchange. In cases where infiltration governs air exchange, the penetration of particles depends on factors such as the geometry of air leakage paths, pressure differentials driving airflow, and the transport properties of the particles. While filters and other cleaning mechanisms help reduce pollutant levels in buildings, various particles and reactive gases can still enter through infiltration pathways. Managing and mitigating pollutant infiltration is essential for maintaining indoor air quality and promoting occupant health and comfort [112,214,215].

In conclusion the building envelope component's part, the building envelope plays a crucial role in shaping the performance, sustainability, and comfort of a structure. Each component, from walls to fenestration, thermal insulation, and infiltration control, contributes to the overall effectiveness of the envelope in regulating indoor environments and minimizing energy consumption. By understanding and optimizing these components, designers and builders can create buildings that are more energy-efficient, environmentally friendly, and conducive to occupant well-being. Through thoughtful design, careful construction, and ongoing maintenance, the building envelope can serve as a barrier against external elements while promoting indoor comfort, health, and sustainability. Embracing innovative materials, construction techniques, and building practices further enhances the performance and resilience of the building envelope, ensuring its effectiveness over the long term. In essence, prioritizing the design and construction of a high-performance building envelope is essential for achieving sustainable, resilient, and comfortable built environments now and in the future.

2.7 Building Design and Analysis Software

Building energy modeling codes are indispensable tools for assessing a building's energy performance, including energy consumption, HVAC system sizing, lighting requirements, and the feasibility of energy efficiency measures. These codes guide building designers in developing energy-efficient designs and cost-effective retrofits for existing buildings. Developed by different groups, these modeling tools rely on user input data, such as building geometry, construction details, location, mechanical equipment, and building type (residential or commercial), for accurate energy simulations. Additionally, building design and analysis software plays a vital role in modern architectural and engineering practices, facilitating the efficient design, simulation, and analysis of various building aspects, from structural integrity to energy performance and sustainability. Further details can be found in Appendix I.

3 Literature Review: Passive Strategies in Building Design for Energy Efficiency and Sustainability

In recent years, there has been a growing emphasis on designing buildings that are not only aesthetically pleasing but also energy-efficient, sustainable, and conducive to occupant well-being. Passive strategies in building design have emerged as a vital approach to achieve these goals by harnessing natural processes, climate conditions, and architectural elements. This literature review aims to explore the various passive strategies employed in building design, their impacts on energy consumption and indoor comfort, and their contribution to sustainable construction practices.

3.1 Orientation and layout

Orientation and layout stand as cornerstone principles in the realm of sustainable building design, wielding significant influence over energy efficiency and occupant comfort. Givoni's [219] seminal work underscores how proper building orientation optimizes solar exposure, enabling effective utilization of natural daylight and reducing heating and cooling demands. Dutta, Samanta, and Neogi [220] extend this insight to tropical climates, revealing the potential of orientation and movable exterior shading devices to curtail cooling loads. Vasov et al. [221] emphasize the critical interplay between building orientation and envelope characteristics, demonstrating that strategic alignment drives notable variations in energy consumption. Abanda and Byers [222] introduce the power of Building Information Modelling (BIM), showcasing how orientation's impact on energy use can be quantified through virtual analyses.

Figure 3-1 illustrates the building's orientation and the path of the sun during summer and winter, as well as the direction of prevailing winds. Understanding these factors is crucial for optimizing energy efficiency, thermal comfort, and natural ventilation in building design. By analyzing the sun and wind paths, architects and designers can make informed decisions about building orientation, shading strategies, and window placement to maximize natural light, minimize heat gain, and promote passive cooling.

In the context of educational spaces, Buratti et al. [223] illuminate the energy-saving potency of shading devices, glazing systems, and orientation. Through a meticulous study, they establish that the synergistic design of these elements results in substantial reductions in energy consumption. Collectively, these studies underscore that orientation and layout decisions transcend geographical boundaries and technological frontiers. They emerge as essential considerations for architects and designers aiming to achieve sustainable, energy-efficient structures. The literature resoundingly confirms that the judicious alignment of buildings with their environment, coupled with the thoughtful arrangement of internal spaces, holds the key to unlocking enhanced energy performance and ushering in a more sustainable future.

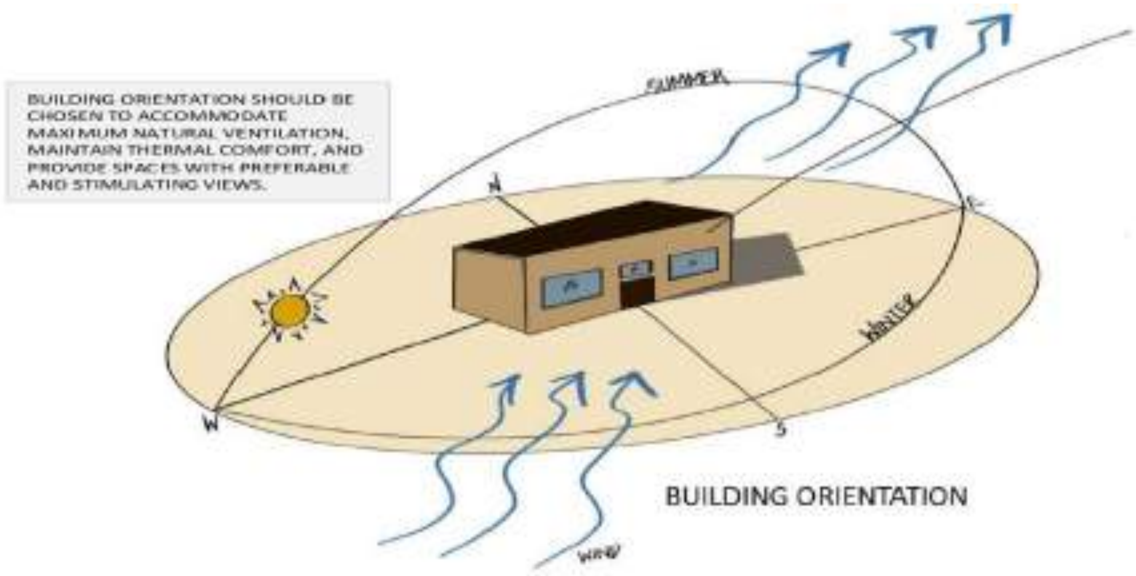


Figure 3-1 Building orientation and environmental analysis [224]

3.2 Insulation and Thermal Mass

Thermal insulation is a simple yet impactful technique for enhancing energy efficiency, effectively reducing both summer cooling and winter heating demands by slowing heat transfer through conduction, convection, and radiation [112]. This importance is underscored by the wide range of insulation materials available, categorized into organic, inorganic, metallic, and advanced types, with selection criteria including thermal conductivity, compressive strength, density, durability, and cost [225-227]. Concurrently, insulation and thermal mass are fundamental aspects of modern building design, crucial for achieving energy efficiency and indoor comfort [228].

The studies examined shed light on thermal insulation materials and thermal mass in building construction, emphasizing their crucial role in bolstering energy efficiency. Covering various topics, including the sustainability aspects of insulation materials, these investigations employ diverse research methodologies such as numerical simulations, experimental analyses, and comparative studies. Their findings offer valuable insights into thermal insulation and glazing technologies in buildings, informing essential considerations for sustainable construction practices.

Akan [229]; Eddib and Lamrani [230] investigated the optimum insulation thickness of buildings in Turkey and Morocco. they use different insulators materials; the selection of insulators is based on the most common in that area. Akan [229] studied life cycle cost analysis and the total annual net savings energy in the buildings. Eddib and Lamrani [230] monitoring indoor environment changes and energy saving. As a result, we notice Rockwool and Wood fiber are the best insulators according to Turkey and Morocco's climate. Daouas [231] used an analytical method based on Complex Finite Fourier Transform (CFFT) to calculate yearly transmission loads for a typical wall structure in Tunisian climate. The study discovered that wall orientation has a negligible impact on optimal insulation thickness but a significant impact on energy savings. The results showed that the south orientation is the most economical with an optimum insulation thickness of 10.1cm, 71.33% of energy savings and a payback period of 3.29 years. Economic parameters, such as insulation cost, energy cost, inflation, and discount rates, were also found to have a noticeable effect on optimum insulation and energy savings.

Huang et al. [232] established a whole-life-cycle assessment model to exploit the optimal economic thickness and evaluated the energy-saving rate, economic benefits, greenhouse-gas emissions. On office buildings in the Chinese zone of a humid subtropical climate, compare the super-insulated aerogel with four commonly-used insulation materials (Expanded Polystyrene, Extruded Polystyrene, Foamed Polyurethane, and Glass Fibers). Thus, aerogel insulation achieved a faster reduction in carbon emissions than other insulators.

Necib, H and Necib, B [233] utilized analytical approaches to computing the optimal insulation thickness using a FORTRAN program. According to the findings, the best insulation thickness for the four East, North, West, and South orientations are 7.3, 6.2, 7.3, and 6.7 cm, respectively. An investigated study was done by Ramin et al. [234] to determine the optimal insulating thickness for various wall orientations In Iran. Furthermore, the effect of the position of the insulation. According to the results, insulation in different wall designs can reduce annual loads by 70–82% compared to an uninsulated concrete wall and 31–58% for an aerated brick wall. Moreover, even though their time lag and decrement factor were not the same, insulation positions resembled yearly loads and ideal insulation thickness.

Yu, S et al. [235] conducted theoretical research to investigate the link between wall insulation and thermal mass and find a balance between wall thermal performance and energy consumption. Using five different materials with varying thicknesses and climates, tracking and analyzing the effects of 4 factors: heat transfer coefficient, thermal inertia index, attenuation degree, and delay time. The result reveals that the correlation coefficient (R2) between M and building energy consumption is around 0.7736–0.8215, which is more than the heat transfer coefficient of 0.3494–0.384 and is more accurate in forecasting building energy needs. Furthermore, the appropriate wall thickness of common building materials in different climate zones is found by analyzing the thermal improvement rate and the building energy-saving rate.

Yu, J et al. [236]; Yu, J et al. [237] devoted their study to finding the optimum insulation thicknesses of five insulation materials, namely Expanded Polystyrene, Extruded Polystyrene, Foamed Polyurethane, Perlite and Foamed Polyvinyl Chloride. For external walls and roofs in 4 different cities in China distinct by hot summer and cold winter. Based on life cycle cost, life cycle saving, payback period analysis. They are considering different orientations, surface colors, insulation materials and climates. Moreover, because of the highest life cycle savings and the lowest payback period, Expanded Polystyrene is the most cost-effective insulating material of the five.

Lamya et al. [238] Their study aimed to investigate the heat transfer through the envelope of an administrative building in Errachidia City in Morocco. The authors used numerical simulation based on the finite element method to evaluate the impact of several thermal insulators, including air, hemp wool, glass wool, rock wool, and extruded polystyrene of different thicknesses, on the heat transfer through the building's envelope. The results showed that air gap is an efficient thermal insulator compared to the other insulators under study. The authors concluded that the use of an air gap as thermal insulation in buildings located in arid regions such as Errachidia City can ensure thermal comfort for occupants, reduce energy consumption, and cut down on material costs.

Evin and Ucar [239] present a methodology for determining the optimum thermal insulation thickness for residential building envelopes. The study includes a case study comparing 4 insulation materials for 20 different energy demand scenarios for four different cities each representing a different climatic zone of Turkey. The study finds that as heating degree-day values increase, required insulation thickness increases, with Van in the cold region requiring the highest insulation thickness. The external wall insulated with rock wool (RW) at the optimum thickness has the least total energy cost among other insulation materials, while the roof insulated with Extruded Polystyrene (XPS) or RW reduces energy cost by 77% and 82%, respectively. RW insulation material in the external wall is the most eco-efficient material among other insulation materials. The study concludes that the methodology can be replicated to other kinds of buildings and different climatic conditions, and that the results will be helpful in guiding the choice of insulation type for building envelopes in different climates.

D'Agostino et al. [240] conducted an analysis of the optimal thermal insulation thickness for an office building in different climates using the "cost-optimal" methodology. They used energy simulations under dynamic conditions for a case study in Palermo, Milan, and Cairo, considering various internal thermal loads and insulation thicknesses. Their findings showed that excessive insulation in buildings with high internal thermal loads or located in hot climates could lead to higher energy consumption for cooling. The optimal insulation thickness varied for each location, with Milan requiring 8-10cm of insulation, Palermo requiring 2-4cm, and Cairo not benefiting from insulation. They also proposed a modified "cost-optimal" methodology that considered thermal comfort, resulting in a different optimal solution for Milan. The study has some limitations and suggests further investigations into cool down by ventilation and insulation with low thermal mass.

Studies by Reilly and Kinnane [241] emphasize the role of thermal mass in stabilizing indoor temperatures, particularly in hot climates, while Sharaf [242] highlights the importance of high thermal mass materials like clay bricks for comfort and energy savings in colder climates. Additionally, research by Zilberberg et al. [243] proposes optimization methodologies integrating structural design and thermal performance, demonstrating the intricate relationship between thermal mass and insulation for enhanced energy efficiency. Innovative approaches, such as incorporating polycarbonate films within glazing systems Li et al. [244], offer tailored solutions for diverse climates, emphasizing the dynamic interplay between insulation and thermal mass in sustainable building design.

3.3 Shading and Solar Control

The importance of shading and solar control techniques in building design for reducing energy consumption is underscored by a collection of research studies. Santamouris et al. [245] emphasize that shading devices like overhangs, louvers, and awnings have significant potential to reduce cooling loads and enhance energy efficiency while maintaining indoor comfort. Al-Masrani et al. [246] focus on tropical office buildings, where conventional shading systems face limitations in controlling solar light. They explore passive, active, and hybrid shading systems, highlighting the rise of hybrid solutions for improved performance in tropical climates. Valladares-Rendón et al. [247] review strategies such as facade self-shading, shading devices, window-to-wall ratio, and building orientation. Their findings reveal that well-designed passive strategies can substantially decrease insolation and lead to notable energy savings. Skarning et al. [248] investigate dynamic solar shading in nearly zero-energy loft rooms, demonstrating its potential to reduce overheating and increase daylighting, but cautioning that its impact on space-heating demand is less predictable. Collectively, these studies underscore the pivotal role of shading and solar control techniques in achieving energy-efficient and comfortable built environments, urging careful consideration of design parameters and strategic placement for optimal results. Alwetaishi et al. [249] and Buratti et al. [250] further accentuate the critical role of shading devices, particularly in educational buildings, where strategic implementation yields remarkable reductions in energy consumption, up to 29%, through meticulous design considerations and placement. In sum, these studies collectively underscore the pivotal role of shading and solar control techniques in realizing energy-efficient and comfortable built environments, advocating for their careful integration and deployment to optimize results.

Figure 3-2 depicts the orientation and types of shading devices, along with the optimal choice of direction for their installation. By considering factors such as solar exposure and building orientation, designers can select the most appropriate shading devices and orientations to enhance occupant comfort, minimize energy consumption, and promote sustainable building practices [251].

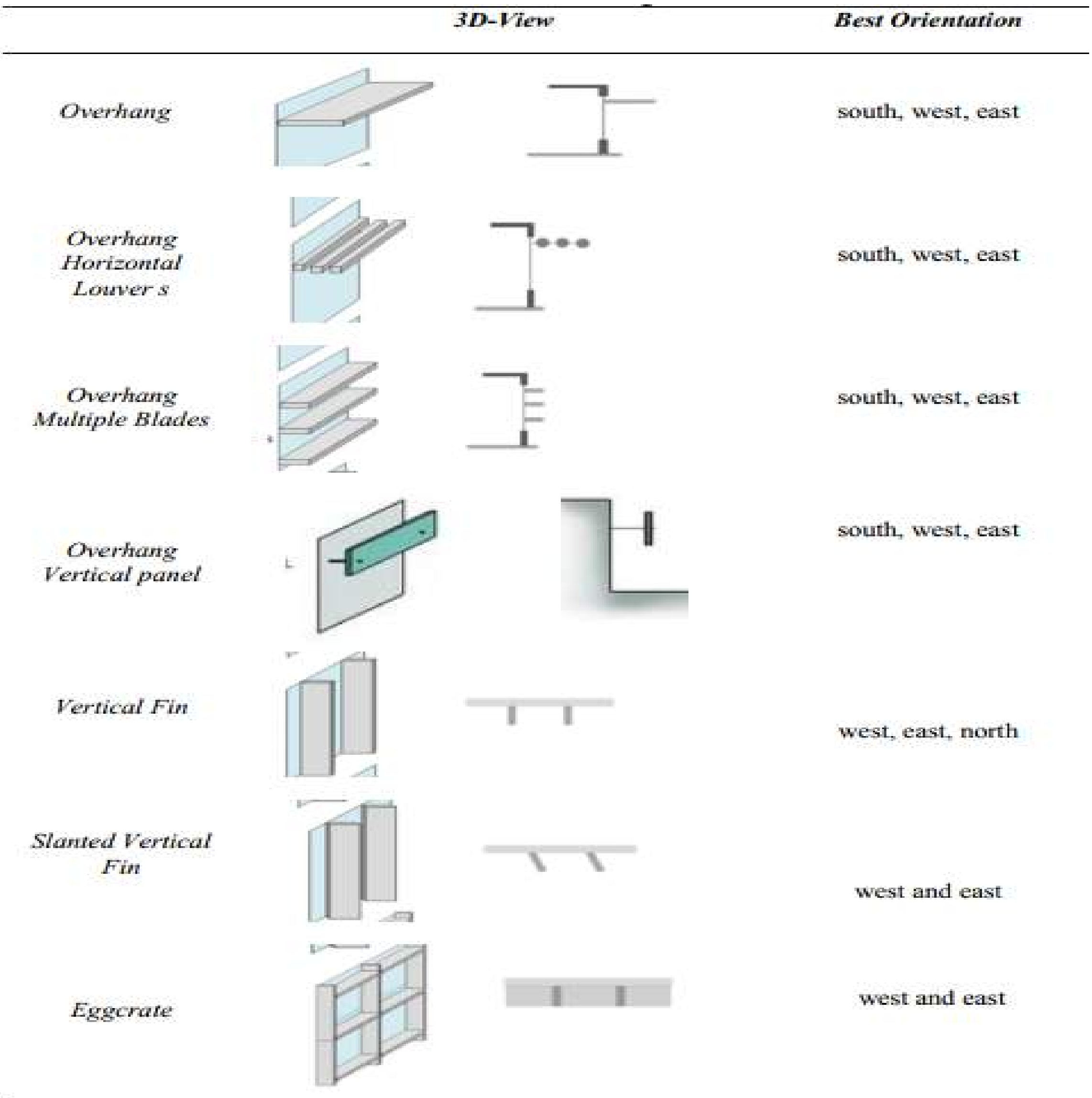


Figure 3-2 Types of shading devices and their optimum orientation [251]

Horizontal Shading is often used on the southern side because the angle of projection to the sun's rays is large in the winter season and vice versa for the summer. When designing shading devices, the efficacy of shading a window throughout the year depends on the angle the device creates. Typically, the Vertical Shading Angle (VSA) is utilized for horizontal shading devices, while the Horizontal Shading Angle (HSA) is employed for vertical shading device design. Calculating the period of the year during which a shading device provides coverage can be accomplished through various methods. One widely utilized approach is the use of shading masks, which visually represent the portions of the sky visible from a specific point in the model. By overlaying this information onto a sun-path diagram, it becomes possible to determine when the point is shaded or exposed throughout the year.

Figure 3-3 illustrates the process of calculating the Vertical Shading Angle (VSA) and horizontal Shading Angle (HSA) for shading devices. Understanding these angles and masks is essential for optimizing the performance of shading systems in buildings, aiding in the reduction of solar heat gain and glare while maximizing natural light and energy efficiency [252].

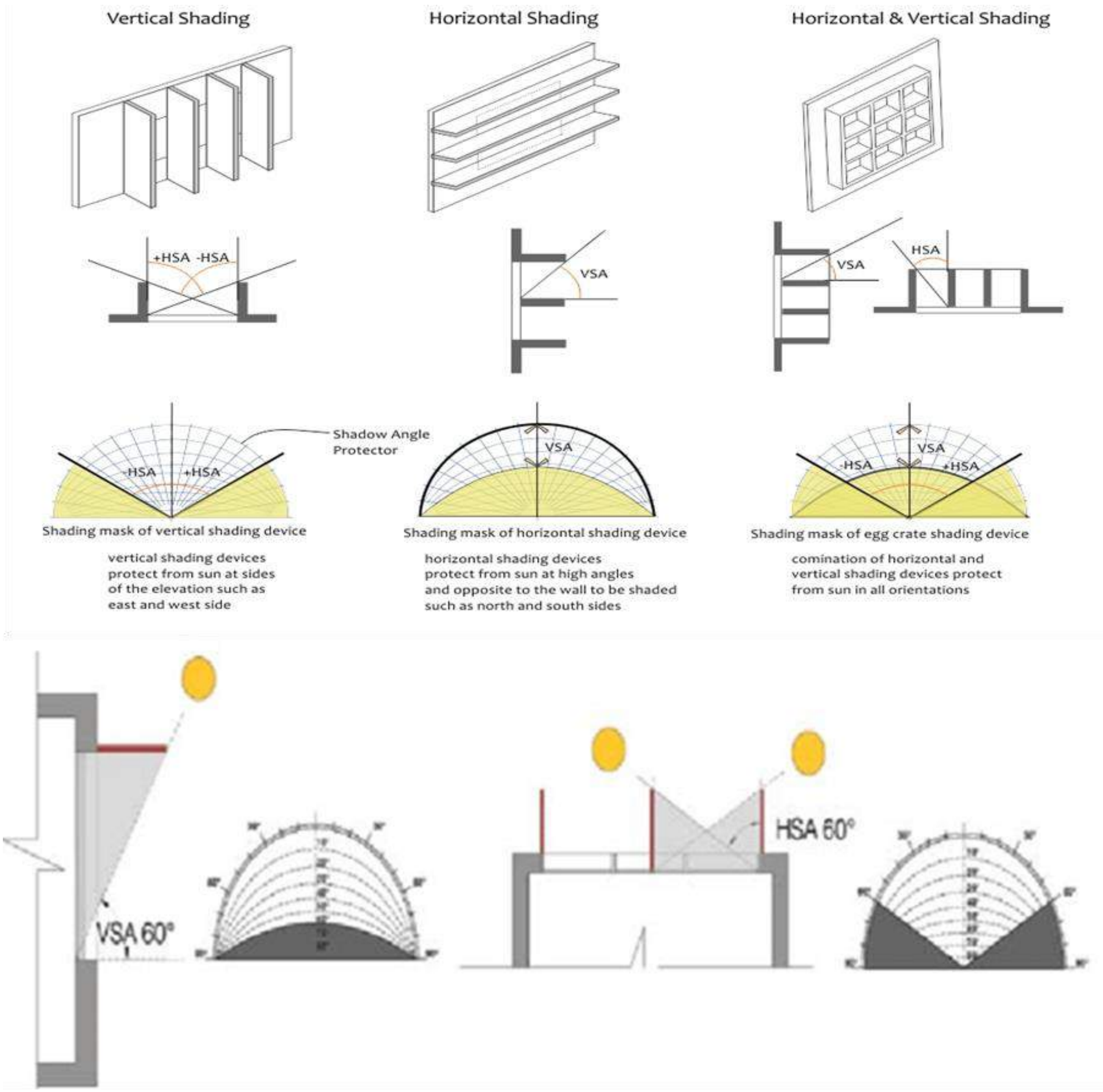


Figure 3-3 Schematic for calculating VSA, HAS [252]

3.4 High-Performance Windows

Windows are crucial components of the building envelope, susceptible to significant heat loss and gain, thus consuming substantial electrical energy [173]. Advancements in glazing technology have led to the development of smart, passive, and active windows, which not only reduce energy demands but also enhance the indoor environment. Understanding the impact of glazing on the building envelope is essential for improving energy efficiency, enhancing thermal performance, and ensuring occupant comfort. Research emphasizes the critical influence of glazing configurations and shading strategies on building energy efficiency. For instance, studies in Saudi Arabia underscore the importance of tailoring glazing-to-wall ratios to local climate conditions to minimize heat gain and loss [253]. Additionally, investigations in Bangladesh highlight the energy-saving potential of integrating external shading and diverse glazing options [254]. Recent studies, including Zouini and Mohammed [255], Somasundaram et al. [256], Ma et al. [257], and Qahtan [258], underscore the importance of glazing optimization and retrofit solutions for enhancing energy performance and occupant comfort. These findings emphasize the critical role of high-performance windows and shading techniques in advancing sustainable building practices [259].

Rezaei, et al. [173] review conventional, advanced, and smart glazing technologies and materials to improve indoor environments and reduce energy consumption in buildings. The authors highlight the importance of windows in energy consumption and CO2 emissions and discuss the relative merits of various glazing systems. They also suggest suitable smart technologies for hot, cool, and temperate climates and emphasize the importance of high visible transmittance and low overall heat transfer coefficient in an ideal window.

Hee, et al. [260] studied the impact of window glazing on energy consumption and occupant comfort in buildings. The authors emphasized the importance of natural light and the challenges of selecting an appropriate glazing that meets both energy and daylighting requirements. The study concluded that optimization techniques can balance the trade-offs between energy and daylighting requirements and that techno-economic evaluation is important to determine the suitable glazing for a building. Finally, the study suggested that dynamic glazing is more suitable for commercial buildings, while static glazing requires more substantial optimization.

Almarzouq and Sakhrieh [261] examined the impact of glazing design and infiltration rate on energy consumption and thermal comfort in residential buildings. They examined a residential building in Amman, Jordan. To identify the best alternative design to minimize energy consumption and improve the indoor environment. The results revealed that replacing a single glazing window with a double-glazing window Argon-filled with low emissivity coating may save 24.7% of the spent energy while degrading thermal comfort by 1%. In addition, a reduced infiltration rate by 50% can save 19.4% of the energy used and enhance thermal comfort by 10%.

Chen et al. [262] conducted a pilot study to investigate the effects of glazing types and daylight on participants satisfaction and performance in a full-scale office in Beijing. Five glazing systems were tested during the heating season, and research methods included lighting measurements, subjective assessments, and reaction time tests. The study found that daylight illuminance associated with glazing types and times of day played a major role in influencing participants visual performances, alertness, physical well-being, and relaxation. The glazing type and correlated color temperature (CCT) of daylight did not significantly affect visual responses if proper daylight illuminance could be achieved. Circadian Stimulus (CS) delivered by daylight varied in times of the day and glazing types, affecting participants alertness and relaxation. Some glazing types could improve physical comfort and reaction time under varying daylight illuminances. However, the study's conclusions were limited to specific climate conditions, one office room, and several typical glazing types, and the impact of seasonal affective disorders was not fully considered. The authors recommended a larger range of glazing types and more accurate investigation tools for future studies.

Alam and Islam's [254] research paper investigate the effect of external shading and window glazing on energy consumption of residential buildings in Jessore, Bangladesh. The study employs EnergyPlus software to evaluate the impact of shading and glazing on the energy transferred into or lost from the room through the fenestration areas. The authors conclude that appropriate overhangs or side fins can significantly reduce the annual energy transferred into the building. They also found that shaded simple glazing can have an energetic behavior equivalent to high-performance glazing, leading to a reduction in cost. The study suggests that selecting the best window with different glazing, overhangs, and side fins based on energy evaluation is achievable.

Dutta and Samanta [263] compared two popular building simulation models, TRNSYS and eQUEST, to assess their relative accuracy in simulating a multizone building located in a tropical climate. Both models were validated using actual and simulated annual energy consumption data, and a model-to-model comparison was performed. The results showed that TRNSYS predicted the building's total energy consumption more accurately than eQUEST. The study also investigated the energy-saving potential of five different types of single- and double-glazing glasses using both simulation models. The findings revealed that the solar heat gain coefficient (SHGC) was a more important factor than U-value in reducing the cooling load of the building's energy. The study concluded that both simulation models are capable of generating building models similar to the actual case building, and that the proper selection of window glazing can significantly reduce energy consumption in tropical climates.

3.5 Passive Solar Heating

The critical significance of passive solar heating in reducing energy consumption in buildings. Passive solar heating harnesses solar energy through south-facing windows and thermal mass, gradually releasing it during colder periods. Szokolay [228] and Olgyay [264] discuss the principles and successful applications of passive solar design, emphasizing its potential to achieve energy-efficient thermal comfort. Liu et al. [265] analyze the suitability and impact of passive solar technologies in Tibet's climate, demonstrating substantial energy-saving rates in specific zones. Albayyaa et al. [266] evaluate various design strategies in residential buildings, revealing that incorporating passive solar techniques and higher thermal mass can significantly reduce heating energy requirements. Collectively, these studies underscore the pivotal role of passive solar heating as a sustainable and effective approach to enhance energy efficiency and indoor comfort in diverse building contexts.

3.6 Passive Cooling

Passive cooling techniques in buildings play a pivotal role in energy conservation and maintaining thermal comfort. Bhamare et al. [267] provide a comprehensive review, emphasizing the applicability of passive cooling techniques in different climatic zones. Their analysis underscores the potential of these techniques to reduce building energy consumption while effectively managing indoor temperatures. Firfiris et al. [268] extend the discussion to livestock buildings, highlighting the unique considerations for farm animals and the energy-saving benefits of passive cooling systems. Their critical review not only evaluates the effectiveness of various cooling systems but also suggests the adoption of similar techniques used in urban buildings for sustainable farming. Additionally, Chan et al. [269] focus on potential passive cooling methods based on radiation controls, such as thermochromic smart windows, daytime radiative coolers, and reflective paints. Their review discusses the integration of these technologies with building facades and emphasizes their role in mitigating solar radiation absorption, thus reducing the dependence on artificial cooling and contributing to carbon neutrality.

3.7 Daylighting & Natural Daylight

3.7.1 Daylighting

The pivotal role of daylighting in mitigating energy consumption while enhancing occupant well-being in buildings. It underscores the symbiotic relationship between effective daylighting design and energy savings, as demonstrated by Mardaljevic and Heschong [270] and stresses the significance of integrating light-colored finishes, reflectors, and light shelves for optimal results. Costanzo et al.'s studies [271,272] emphasize climate-based metrics and shading solutions for educational environments, accentuating the need for a holistic approach. Fakhari et al. [273] underscore the multi-dimensional impact of various factors on visual comfort, advocating for comprehensive design considerations beyond energy conservation. Soleimani et al. [274] exploration of heritage buildings emphasizes the synergy of glazing patterns and shading systems for improved daylight distribution and user comfort. Lastly, Abdelhakim et al. [275] stress the importance of tailored glazing configurations and shading devices, catering to climatic conditions and occupant needs. Together, these studies underline the multifaceted significance of daylighting in promoting sustainable and comfortable indoor environments while addressing energy efficiency concerns.

3.7.2 Natural Daylight

The importance of natural daylight in buildings is a critical aspect of modern architectural design, driven by the pursuit of sustainability and occupant well-being. Various strategies, including light wells, clerestory windows, and light tubes, are employed to channel daylight into deep interior spaces. The overarching goal is to create intelligent, energy-efficient buildings that enhance the comfort of occupants. One avenue of exploration in this domain is daylighting design, as discussed in by Wong [276]. The paper critically reviews and compares daylighting design principles, technologies, and calculation methods, providing valuable insights for engineers and designers aiming to assess the applicability of daylighting systems in different building types. Vaisi and

Kharvari [277] delves into the evaluation of daylight regulations, specifically assessing the Window to Floor Ratio (WFR) using Daylight Factor (DF) analysis. The study proposes an optimal WFR range based on international standards, addressing concerns related to glare and overheat. In a broader exploration, by Tabadkani et al. [278] emphasizes the psychological well-being impacts of daylight exposure. The study reviews available daylighting systems, their adaptation features, and quantitative indices related to visual comfort, revealing challenges in establishing universally accepted illuminance thresholds and reliable glare indices. These research contributions collectively underscore the multifaceted importance of natural daylight in building design, addressing technical, regulatory, and human-centric aspects.

3.8 Cool Roofs and Green Roofs

Cool roofs and green roofs represent innovative strategies at the forefront of sustainable building practices. Akbari et al. [279] underscore cool roofs' significance in offsetting CO2 emissions through reflective materials that mitigate urban heat island effects and reduce cooling demands. Bozonnet et al. [280] French case study demonstrates cool roofs' efficacy in enhancing building thermal response, particularly in summer conditions, underscoring their potential in diverse climates. Shafique et al, [281] highlight green roofs' multi-faceted benefits, addressing urbanization challenges through stormwater reduction, improved air quality, and energy efficiency, despite initial hurdles. Besir and Cuce [282] comprehensively review green roofs and facades, spotlighting their substantial role in curbing energy consumption by enhancing thermal performance and mitigating greenhouse gas emissions. Together, these studies emphasize the transformative potential of cool roofs and green roofs, making strides toward resilient, energy-efficient, and sustainable urban environments.

3.9 Natural Ventilation

Natural ventilation promotes fresh airflow, improving indoor air quality and reducing energy usage [283-287].

Natural ventilation is a crucial strategy for reducing energy consumption in buildings. Humphreys and Nicol [283] emphasize the advantages of well-designed openings to facilitate fresh air flow, highlighting techniques like cross-ventilation and stack ventilation. Zhang et al. [284] critically review integrated natural ventilation systems, revealing their potential for surpassing single systems in performance, heat recovery, and energy efficiency. Wang and Malkawi [285] propose a Design-Based Natural Ventilation Potential index, catering to early-stage design considerations and promoting energy-efficient naturally ventilated buildings. Chen et al. [286] assesses global natural ventilation potentials, emphasizing the impact of local climates on system effectiveness and providing guidance for tailored designs. Gil-Baez et al. [287] stress the viability of natural ventilation in near-zero energy schools, showcasing substantial energy savings and improved indoor comfort. Collectively, these studies underscore the importance of natural ventilation in achieving energy-efficient, comfortable, and environmentally friendly built environments.

3.10 Thermal Chimneys

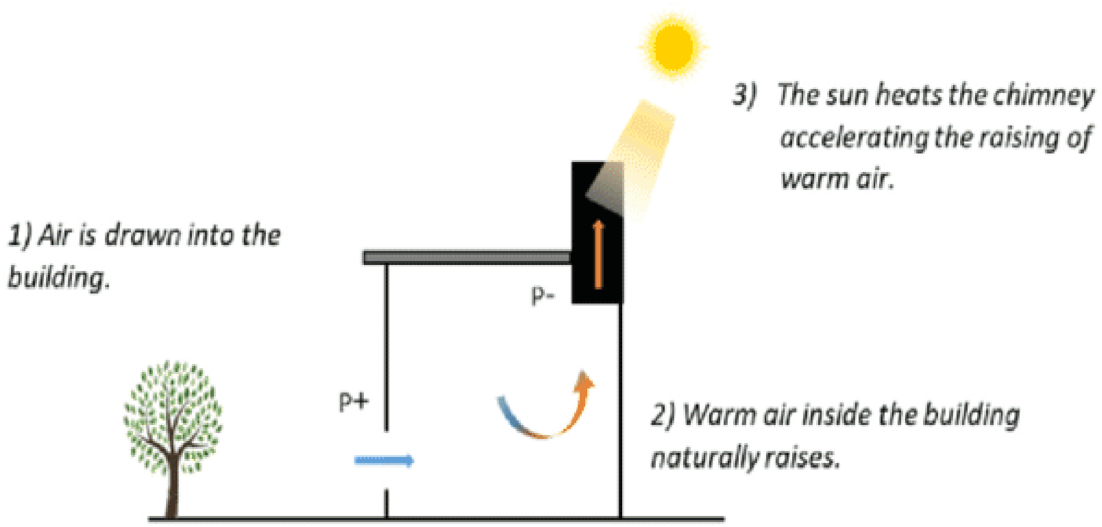


Figure 3-4 Solar chimney operating principle [288]

Thermal chimneys are vertical areas that utilize the stack effect to improve natural ventilation, and they are crucial in passive design solutions for energy-efficient buildings, as depicted in Figure 3-4. In their study, Monghasemi and Vadiee [289] provide a thorough examination of solar chimney integrated systems, with a particular focus on their ability to enhance thermal comfort in residential areas while reducing energy usage. The study explores different integrated configurations, emphasizing the necessity for additional experimentation and optimization methodologies. In their study, Cottam et al. [290] investigate how the shape of the canopy affects the performance of solar thermal chimneys. They suggest a design with a slightly sloping canopy that performs well even in different environmental situations. Their discoveries emphasize the importance of the height of the canopy in optimizing the kinetic energy required for efficient chimney functioning. Lee and Strand [291] enhance the existing body of knowledge by creating a module for EnergyPlus that models the energy effects of thermal chimneys. They examine variables such as chimney height and solar absorptance. Their research demonstrates the capacity for substantial reductions in cooling energy use by effectively utilizing thermal chimneys, highlighting their effectiveness in improving natural airflow. The study contributions emphasize the significance of thermal chimneys in sustainable building design, providing valuable insights into their structures, optimization of performance, and potential for energy conservation.

3.11 Earth Sheltering

Earth sheltering is an environmentally conscious construction technique that utilizes the earth's natural heat to save energy usage and improve the temperature conditions inside structures. In their study, Doraj et al. [292]explore the notion of "Earth-Shelter Architecture," focusing on its historical origins and current relevance in tackling climatic difficulties. The study promotes the incorporation of the earth's thermal mass into architectural buildings to achieve thermal comfort. It suggests methods to utilize the earth's thermal stability effectively. Khaksar et al. [293] provide valuable insights through a case study conducted in Meymand, Iran, where they evaluate the thermal comfort of structures constructed with earth-sheltered techniques. Their research utilizes simulation tools and adaptive thermal comfort models to optimize architectural layouts, resulting in a significant 31% improvement in annual thermal comfort. Staniec and Nowak [294] conducted a more in-depth investigation into the energy dynamics of earth-sheltered buildings. They specifically analyse the heating and cooling energy requirements, taking into account different types of soil. Their study highlights the significant impact of soil type on the annual energy balance of earth-sheltered buildings, underlining the crucial role of soil features in the design process. These study contributions jointly underline the importance of earth sheltering in optimizing energy usage and promoting thermal comfort in architectural buildings.

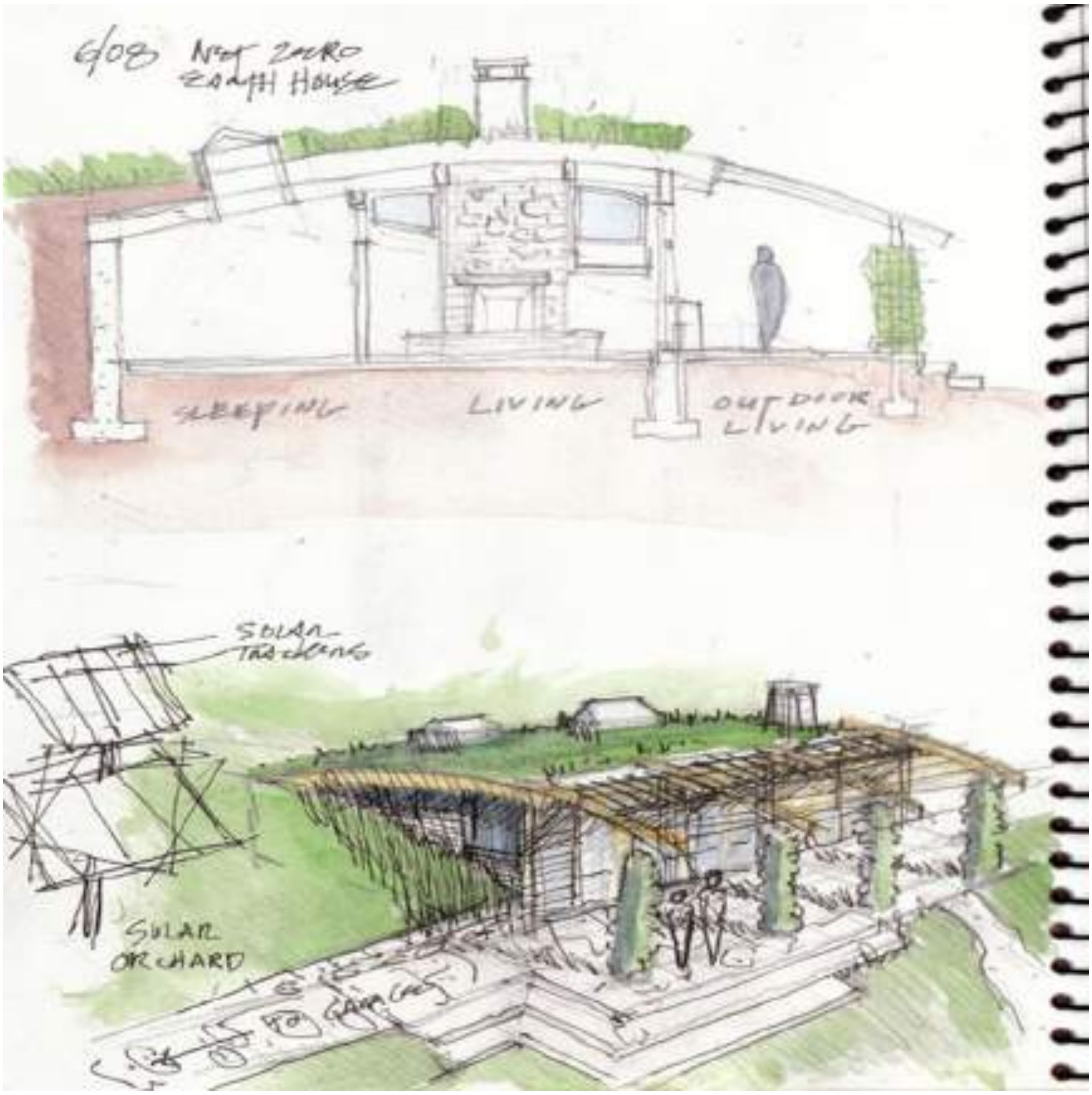


Figure 3-5 Sketch of an earth-sheltered house [295]

3.12 Energy-Efficient Landscaping

Energy-efficient landscaping plays a crucial role in the sustainable development of the built environment, combining energy conservation and landscape quality. Ramesh [296] investigates how energy-efficient landscape factors might enhance thermal comfort in urban areas. The inquiry explores the energy-saving capabilities of different ground surfaces, with a particular focus on the use of shading and plants to reduce the heat island effect. Meanwhile, Rao and Gupta [297] emphasize the significance of strategically designed plants surrounding buildings in mitigating the urban heat island effect and reducing power consumption. Their study, provided in the form of a book chapter, examines different landscape typologies and components, and explores diverse approaches and tactics to effectively deal with extreme climatic circumstances. In their study, Yüksek and Karadayi [298] specifically examine the design of energy-efficient buildings throughout their whole lifespan, acknowledging the significant contribution of buildings to worldwide energy usage. This study presents a thorough analysis of energy-efficient guiding principles throughout different stages of a building's life cycle. It offers valuable insights into the substantial potential for decreasing energy consumption in structures [296-298].

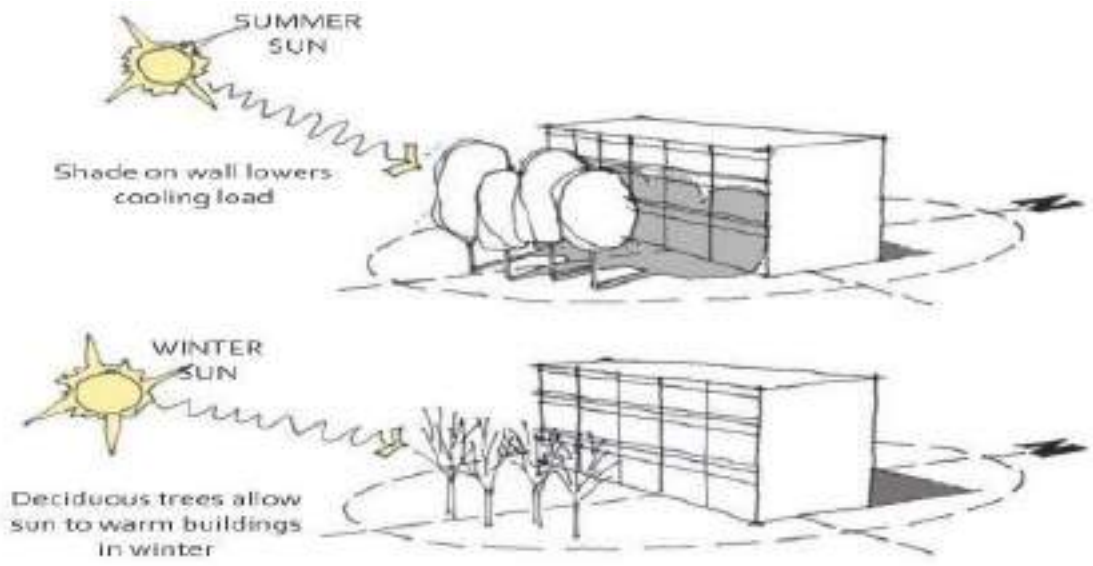


Figure 3-6 Landscape strategies for passive solar heating and day lighting control [299]

In conclusion, Passive strategies in building design offer a promising pathway to achieving energy-efficient, comfortable, and sustainable built environments. Extensive research demonstrates the effectiveness of various passive strategies in reducing energy consumption and enhancing indoor comfort. These strategies contribute not only to immediate energy savings but also to the long-term sustainability of buildings and their positive impact on the environment.

As the construction industry continues to prioritize sustainable practices, the integration of passive strategies and renewable energy in building design is likely to play a pivotal role in shaping the future of architecture and urban development. However, further research and empirical studies are necessary to refine design guidelines, optimize strategies for specific contexts, and continue advancing the field of passive building design.

These passive strategies can collectively contribute to energy savings, reduced environmental impact, and improved occupant comfort in buildings. The specific strategies chosen will depend on factors such as climate, location, building type, and budget.

4 Materials and Methods

4.1 A Multi-Software Approach to Assessing the Energy Performance of Buildings: Using Meteonorm, Climate Consultant, SketchUp, and TRNSYS

In our study, we adopted a multi-software approach to comprehensively assess the energy performance of buildings. By integrating various software tools such as Meteonorm, Climate Consultant, SketchUp, and TRNSYS, we aimed to gain a holistic understanding of the complex factors influencing building energy consumption and efficiency. Meteonorm provided essential meteorological data, allowing us to accurately simulate climatic conditions and solar radiation patterns. Climate Consultant aided in visualizing and analyzing climate data, facilitating informed decisions during the design and analysis phases. SketchUp enabled the creation of detailed 3D models, allowing for realistic building simulations and assessments. Finally, TRNSYS offered advanced energy simulation capabilities, enabling us to evaluate the dynamic interactions between building components and systems.

The selection of these software tools was justified based on their versatility, extensive validation, and industry adoption, allowing us to leverage their strengths for a comprehensive assessment of building energy performance and the development of strategies to improve energy efficiency and sustainability.

The Figure 4-1 illustrates a comprehensive building performance simulation engine. This simulation process involves gathering various inputs such as climatic data, building geometry, material properties, and occupancy patterns. Meteonorm provides weather data, while Climate Consultant aids in visualizing and analyzing the weather data. SketchUp is utilized to generate a 3D model of the building, with assistance from the TRNSYS 3D plugin. These inputs are then fed into the simulation engine TRNSYS, which processes the data to predict the building's performance in terms of energy efficiency, thermal comfort, and other sustainability metrics. The simulation results can inform design decisions and optimizations for enhancing building performance.

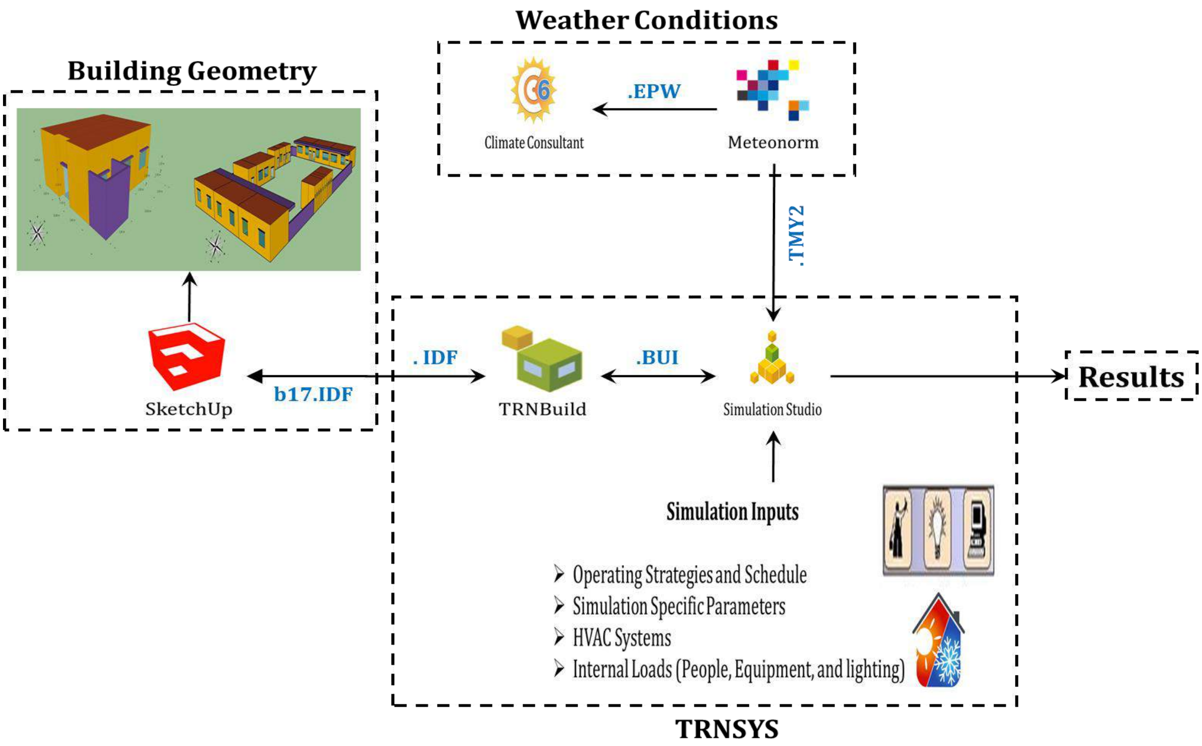


Figure 4-1 Diagrammatic representation of building performance simulation process

4.2 Characterization of the research region's climate

The building envelope's response is primarily determined by the climate. Hence, comprehending climatic conditions is vital for the design of residential buildings and the attainment of thermal comfort. The issue can be defined as the transmission of heat and mass through the envelope, utilizing an initial estimate of the climate. For problems requiring the evaluation of transfers, it is essential to have initial and boundary conditions. However, the appropriate configuration of these circumstances relies on the specific environment of the research region [300,301].

The primary goals of the climatic, bioclimatic, and microclimatic investigations were to analyze and describe the climate, as well as identify the most efficient conceptual methods. The climate is classified as semi-arid based on De Martonne's 1923 [302,303] calculation of the aridity index (IDM), which is determined using the following formula:

$$\mathrm{I_m} = \frac{P}{T+10} \qquad (1)$$

Where $\mathrm{I_m}$ is the annual aridity index, *P* is the total annual precipitation in (mm), and *T* is the annual average temperature in (°C). The value of 10 has been added to the thermometric averages to prevent the index from reaching negative values. The absolute arid, arid, and semi-arid conditions fall between 0 and 20 (where Absolute arid I_m <5, arid 5< I_m ≤10, and semi-arid 10< I_m ≤20. In excess of this threshold conditions are humid (where semi-wet 20< I_m ≤30, wet 30<I_m ≤ 40, and absolute wet I_m > 40). With an I_m of 10.71, the climate is classified as sub-arid.

The village khoualed Abdel Hakem is located in the Wilaya of Ain Temouchent characterized by hot summers and temperate winters. However, the climatic regime characterizes by winds that generally bring little humidity. The average annual temperature is 20.16 °C, and the average precipitation is 323 mm. July is the hottest month of the year. The average temperature is 35.9 °C at this time. In January and December, the average temperature is 6.9 °C. January and December are, therefore, the coldest months of the year. The precipitation difference of 63 mm is the record between the driest month and the wettest month.

The Gaussen aridity index [303-306] has been used to produce the climogram of the village khoualed Abdel Hakem, as illustrated in Figure 4-2. To distinguish between wet and dry months, we use an index that includes monthly average rainfall in (mm) and temperature in (°C). It is defined as follows:

$$P = 2T_m \qquad (2)$$

The given month is considered dry when $P < 2T$, i.e. When potential evapotranspiration (PET) is greater than precipitation. Conversely, when $P > 2T$, the month is considered wet.

This index often illustrates by a diagram called the "Ombrothermic diagram of GAUSSEN." The latter makes it possible to distinguish between the wet period, where $P > 2T$, and a dry period where $P < 2T$.

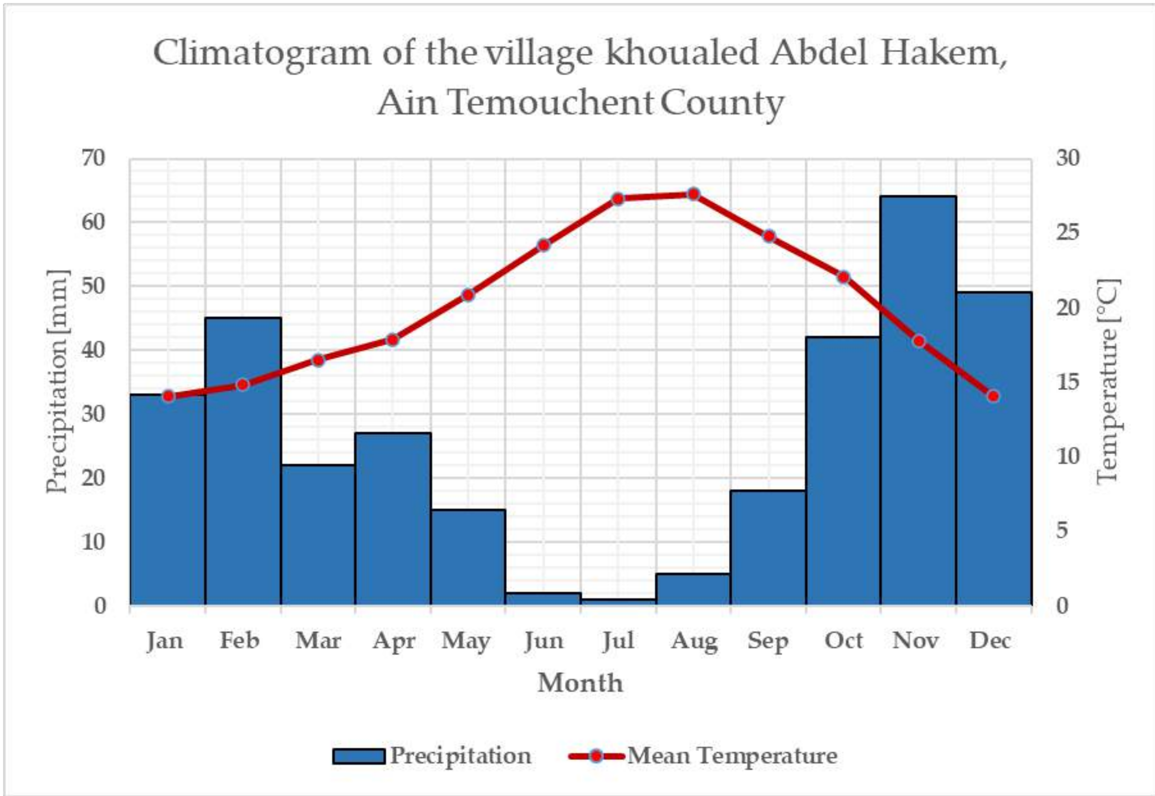


Figure 4-2 GAUSSEN ombrothermic diagram for the village khoualed Abdel Hakem, Ain Temouchent Wilaya

In a Mediterranean context, the village's average ombrothermic diagram represents a drought. Nonetheless, these depictions are merely averages and completely conceal annual variations, which can be locally significant. Overall, the dry season in our study region is quite lengthy, lasting approximately eight months from March to October. From November to February, there is a four-month wet period.

The relative humidity is greater than 76.97% on a monthly basis, with a maximum average of 93.38% and a minimum of 62.08%. The average annual temperature is 20.16 °C, ranging from 27.88° C in August to 13.73° C in January and December. Extreme temperatures range from 6.90° C in January to 35.89° C in July. The average monthly sunshine in the region is 369.45 hr, with a minimum of 303.8 hr in December and a maximum of 449.5 hr in June. The total annual precipitation is 323 mm, with a November maximum of 64 mm. There is a 63 mm difference between the driest and wettest months, and nearly 59% of annual rainfall records occur during the wet season. The mean wind speed in the region ranges from 3.60 to 4.80 m/s, with an annual average of 4.23 m/s. Even though the climate is generally characterized by winds that bring little humidity (winds from the northwest and southeast), these winds lose a significant portion of their moisture as they pass over the Moroccan and Spanish reliefs. In addition, the southern reliefs (SEBAA - CHIOUKH, TESSALA, and MONTS DE TLEMCEN) have a positive impact by preventing the entry of dry and hot continental winds from the south (SIROCCO) [308]. In Appendix III-1, you'll find a concise summary of the weather data about the village Khoualed Abdel Hakem in the Wilaya of Ain Temouchent [309]. For a detailed exploration of the climatic characteristics specific to the studied village, please consult Appendix III-2 [307].

4.2.1 Sun Shading Chart

In analyzing the climatic data for our study, we utilized Climate Consultant 6.0 [309]. This software provided valuable insights into the weather patterns of the studied region.

The Climate Consultant program calculated the duration of shading needed for the simulated building. The simulation findings depicted in Figures 4-3 and 4-4 illustrate the yearly count of hours categorized as hot, cold, and pleasant within the simulated building. During the period from 21 December to 21 June, which encompasses the winter and spring months, there is a requirement for shade for a total of 114 hr. Conversely, there is a need for sunlight for a total of 1522 hr. Additionally, during this timeframe, 876 hr can be considered comfortable. During the summer months, specifically from 21 June to 21 December, the building will need shading for a total of 887 hr. Additionally, the building will require direct solar radiation for heating purposes for 516 hr. The remaining 1195 hr of the year are considered comfortable.

Moreover, based on the data presented in Figures 4-3 and 4-4, it can be inferred that the Primary school, categorized as a low-rise non-residential structure, requires shade devices for a total of 1001 hr annually.

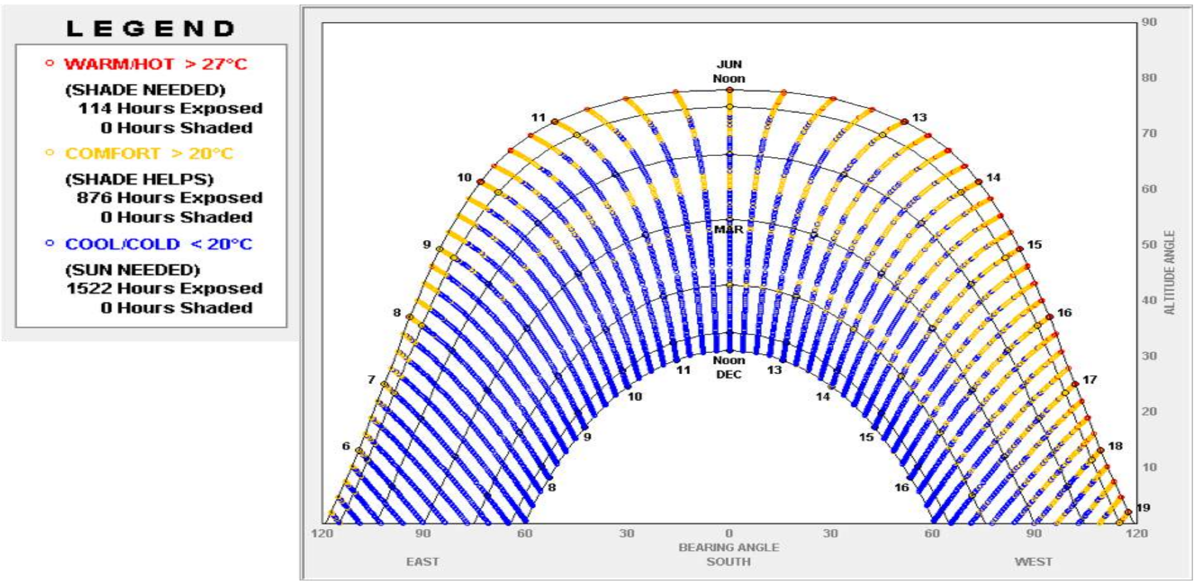


Figure 4-3 Sun shading chart in winter and spring (21 December to 21 June)

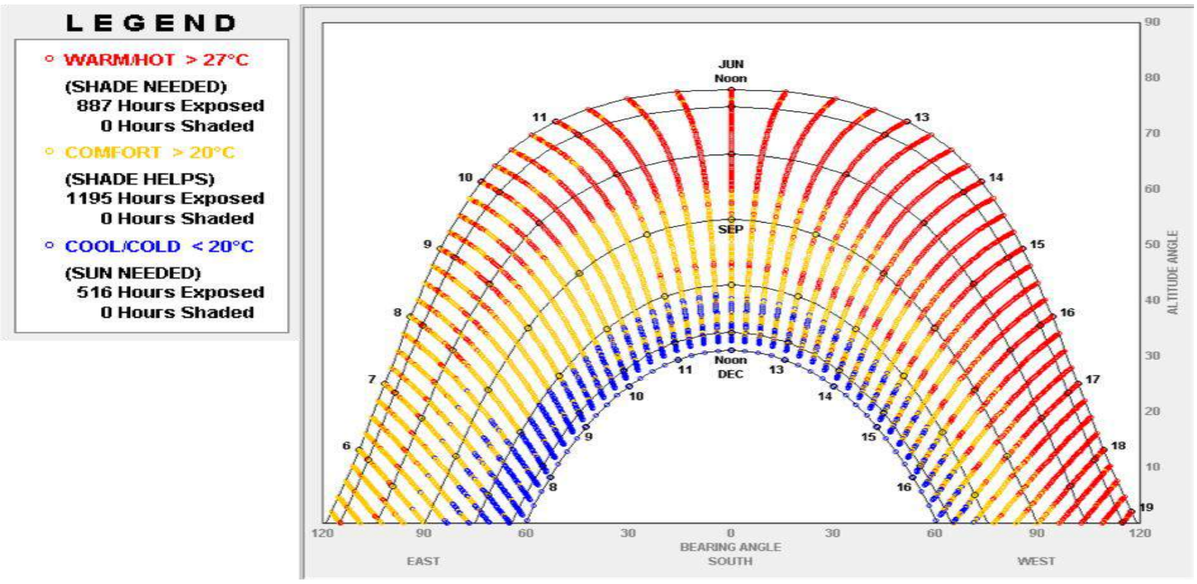


Figure 4-4 Sun shading chart in summer and fall (21 June to 21 December)

4.2.2 Psychrometric Chart

The psychrometric chart is a crucial result generated by the Climate Consultant software. In addition to just displaying meteorological data, the psychometric chart serves to arrange the information in a manner that is clear and accessible, enabling individuals to comprehend the impact of climate on the surrounding environment. Figure 4-5 displays the Comfort Zone, which represents the psychrometric chart for the specific region under study. The building's comfort zone occupies a relatively small area (15.5%), indicating that a substantial quantity of energy would be required for heating and cooling purposes. Hence, it is imperative to develop highly effective passive and active design strategies to address the heating and cooling issue.

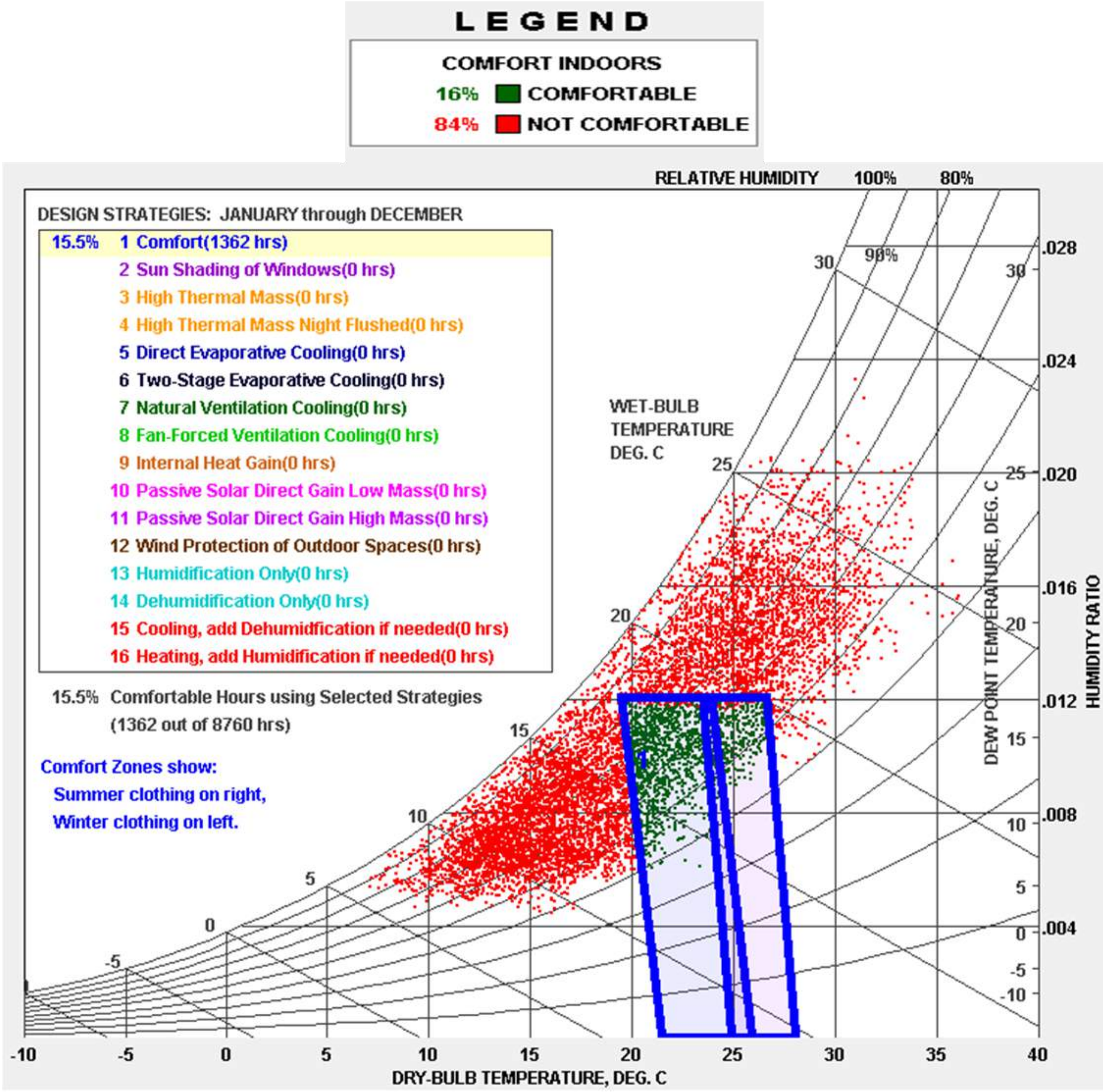


Figure 4-5 Psychrometric chart for village khoualed Abdel Hakem: Comfort Zone

Figure 4-6 illustrates the optimal design solutions for constructing building envelopes in the village khoualed Abdel Hakem. The strategies have the capability to alter or screen extreme external climate conditions in order to establish pleasant inside settings in the village khoualed Abdel Hakem.

The design strategies for the simulated building are outlined as follows:

- *Sun shading of windows:* Figure 4-6 shows that the windows are shaded for approximately 15.6% of the year, which is equivalent to around 1363 hr. By employing shade devices, a total of 1363 hr of discomfort are transformed into hours of comfort.

- *High thermal mass:* The effectiveness of high thermal mass as a cooling design strategy in hot, dry summers and mentioning that the need for high thermal mass is approximately 22 hr, accounting for 0.3% of the entire year.
- *Fan-forced ventilation cooling:* plays a role for 45 hr, constituting 0.5% of the yearly requirements.
- *Internal heat gain:* accounts for 41.4% of thermal comfort and is generated by artificial lighting, electrical equipment, and indoor activities performed by occupants within the structure. This refers to around 3630 hr in a year.
- *Passive solar direct gain high mass:* refers to the total duration in a year during which thermal comfort is attained solely by passive solar gain. This comprises a cumulative duration of approximately 1679 hr, which accounts for 19.2% of the total.
- *Dehumidification:* is an essential component for maintaining thermal comfort in the building for an estimated duration of 1759 hr annually, constituting 20.1% of the total.
- *Cooling, add humidification if needed*: To ensure optimal comfort, it is necessary to implement both cooling and humidification simultaneously. This comprises a cumulative duration of 1326 hr, which accounts for 15.1% of the entire year.
- *Heating, add humidification if needed:* To promote comfort, this technique involves the use of mechanical heating to increase the air temperature, as well as the addition of humidification if necessary. This comprises a cumulative duration of 432 hr throughout the year, which accounts for 4.9% of the entire time.

In consideration of comfort optimization within the studied climate, reference is made to the findings in Appendix III-3. The appendix details the outcome of selecting design strategies based on the Psychrometric Chart, ensuring that 100.0% of the hours are deemed comfortable. This comprehensive list of Non-Residential design guidelines is tailored to the unique characteristics of the climate under investigation. It further provides a month-by-month breakdown of the 20 selected design strategies, ranked in order of importance, with the fourth column highlighting the strategies chosen for the entire year [309].

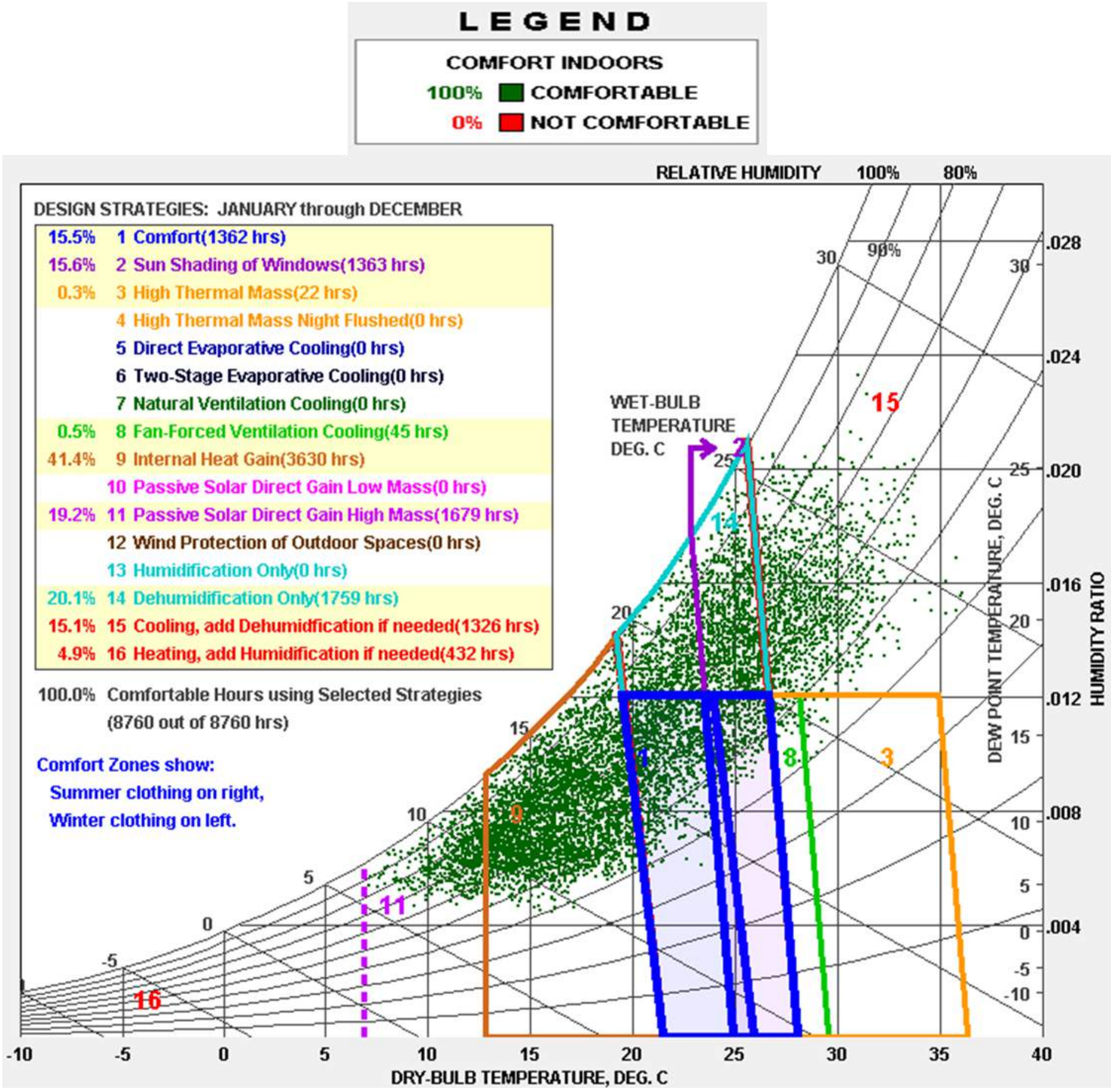


Figure 4-6 Psychrometric chart for village khoualed Abdel Hakem

4.3 Diagnosis of the envelope materials and properties

4.3.1 Traditional house

The following tables provide a comprehensive overview of the thermophysical properties of various building components, including walls, roofs, insulators, windows glazing, and operational data. These tables offer detailed information on the thermal characteristics of these elements, including thermal conductivity, Thermal Capacity, Density, and other important parameters. This data is crucial for designing and constructing energy-efficient buildings that can effectively regulate indoor temperatures and reduce energy consumption.

Table 4-1 summarizes the thermal and physical properties of building construction materials, along with the thickness of each layer of building materials used for both walls and roofs. The information presented in the table provides a detailed overview of the layers of materials used in the construction of these building components, starting from the inside to the outside [310-312].

Table 4-1 Layers and thermophysical properties of building materials

External walls				
	Thickness	**Thermal Conductivity**	**Thermal Capacity**	**Density**
	[cm]	**[W/m. K]**	**[KJ/Kg. K]**	**[Kg/m^3]**
Plaster	1	0.351	1	1500
Parping	20	1.053	0.65	1300
Cement mortar	2	1.15	1	1700
Concrete	2	1.755	0.65	2100
Internal walls				
Mortar	2.5	1.15	0.84	2000
Hollow Brick	10	1.15	0.878	1800
Mortar	2.5	1.15	0.84	2000
Roof				
Plaster	1	0.351	1	1500
Polystyrene	4	0.0361	1.25	25
Reinforced Concrete	4	1.755	0.92	2300
Hourdis	16	1.23	0.65	1300
Reinforced Concrete	4	1.755	0.92	2300
Cement Mortar	10	1.15	1	1700
Floor Tile	1	1.75	0.7	2300

The thermal conductivity, thermal capacity, and density of various insulation materials are listed in Table 4-2. These properties are important for selecting the most appropriate insulation material for a building, as they determine how well the material will perform in terms of heat retention and energy efficiency [310,311].

Table 4-2 Properties of insulation materials [310,311]

	Thermal Conductivity	**Thermal Capacity**	**Density**
	[W/m. K]	**[KJ/Kg. K]**	**[Kg/m^3]**
Expanded Polystyrene	0.0442	1.45	20
Glass Wool	0.0417	0.84	12
Rock Wool	0.0444	0.92	300
Wood Fibre	0.0383	1.95	180

Table 4-3 provides a detailed list of features for each glazing and frame, including the overall heat transfer coefficient and solar energy transmittance. These properties are important for selecting the most suitable glazing and frame for a building, as they determine how much heat is transmitted through the glass and frame and how much solar energy is absorbed [310,312].

Table 4-3 Properties of glazing alternatives

	U-Value [1]	g-Value [2]	Frame	Frame U-Value
Simple	5.74	0.87	Aluminium	2
Double	2.95	0.777	Aluminium	2
Triple	2	0.7	Aluminium	2
Double, Low-e	1.76	0.597	Aluminium	2
Double, Low-e, Ar	1.43	0.596	Aluminium	2

[1] *U-Value: Overall heat transfer coefficient, [W/m²·K].*
[2] *g-Value: Solar energy transmittance of windows, [%100].*

Table 4-4 provides detailed information regarding the orientation, length, and width of windows in a building. The table also contains the position of each window, which indicates the window's height from the ground. These factors are essential for determining the amount of natural light and ventilation that enters the building through the windows.

Table 4-4 Windows orientation and dimensions

Zones	Orientation	Height x Width [m]	Position [1] [m]
Kitchen	South	1.20 x 1.50	1.10
Dining Area	South	1.20 x 2.0	1.10
Room 01	South	1.20 x 1.50	1.10
Bathroom	East	0.8 x 0.8	2.0
Room 02	East	1.20 x 1.50	1.10
Living Area	North	1.20 x 1.50	1.10
Guests Room	North	1.20 x 1.50	1.10

Table 4-5 presents the operational data for the studied house and includes important details regarding the comfort temperature range for both winter and summer, as defined by ASHRAE criteria [313]. Additionally, the table provides information on the set temperature for heating and cooling settings, which is essential for ensuring optimal thermal performance and energy efficiency in the building.

Table 4-5 The operational data

Temperature Set Range [1]	Winter	20.3-24.3 °C
	Summer	24.3-26.7 °C
Heating Set Point	20.3°C	
Cooling Set Point	26.7°C	

[1] *Comfort temperature range selected according to ASHRAE criteria [314]*

4.3.2 Primary school

The tables below illustrate all the thermophysical properties of walls, roofs, windows design, and operational data. We take the thermo-physical properties of construction materials from the library TRNSYS17 software, which is very rich [310].

The thermal and physical properties of building construction materials, the thickness of each layer of building materials used for walls and roof, are summarized in Table 4-6, from the inside to outside [310-312].

The composition of the school's walls is meticulously detailed in Table 4-6, presenting a comprehensive overview of the thermal and physical properties of various construction materials. The table is structured to delineate the thickness, thermal conductivity, thermal capacity, and density for each layer of the external walls, internal walls, and roof. Beginning from the innermost layer, the external walls comprise plaster, parping, an air gap, parping again, cement mortar, and concrete, each with distinct properties contributing to the overall performance of the building envelope. Moving to the internal walls, the composition includes mortar, hollow brick, and mortar, each layer carefully chosen to balance structural integrity and thermal considerations. The roof, crucial for maintaining overall energy efficiency, consists of plaster, reinforced concrete, hourdis, reinforced concrete again, and cement mortar. This detailed breakdown, organized from the inside to the outside, serves as a valuable reference for understanding the layered composition and thermal characteristics of the school's walls.

Table 4-6 Layers and thermophysical properties of building materials

	Thickness	**Thermal Conductivity**	**Thermal Capacity**	**Density**
	[cm]	**[W/m. K]**	**[KJ/Kg. K]**	**[Kg/m3]**
External walls				
Plaster	1	0.351	1	1500
Parping	10	1.113	0.65	1300
Air Gap	10	0.778	1.227	1
Parping	10	1.113	0.65	1300
Cement mortar	2	1.15	1	1700
Concrete	2	1.755	0.65	2100
Internal walls				
Mortar	2.5	1.15	0.84	2000
Hollow Brick	10	1.15	0.878	1800
Mortar	2.5	1.15	0.84	2000
Roof				
Plaster	1	0.351	1	1500
Reinforced Concrete	4	1.755	0.92	2300
Hourdis	16	1.23	0.65	1300
Reinforced Concrete	4	1.755	0.92	2300
Cement Mortar	10	1.15	1	1700

Table 4-7 lists the features of each glazing design and frame, which are overall heat transfer coefficient and solar energy transmittance [310,312].

Table 4-7 Properties of glazing

	U-Value [1]	g-Value [2]	Frame	Frame U-Value
Single-layer	5.74	0.87	Aluminum	2
Single-layer	5.74	0.87	Wood	2.27
Double	2.95	0.777	Aluminum	2
Double, Low e	1.76	0.597	Aluminum	2
Triple	2	0.7	Aluminum	2

[1] *U-Value: Overall heat transfer coefficient, [W/m²·K].*
[2] *g-Value: Solar energy transmittance of windows, [%100].*

Table 4-8 displays the windows orientation, length, and width. Where position refers to the window height from the ground level.

Table 4-8 Windows orientation and dimensions

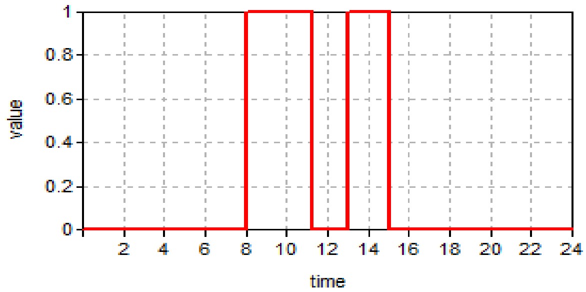
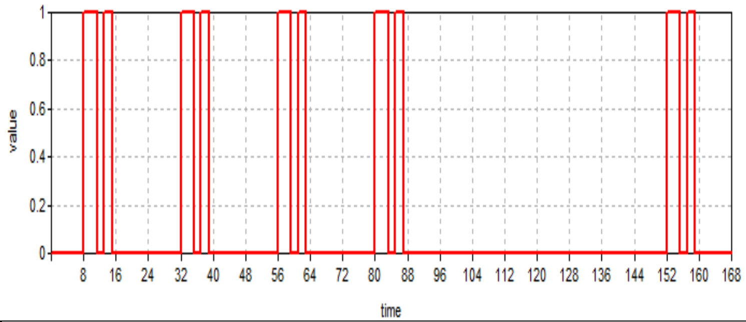
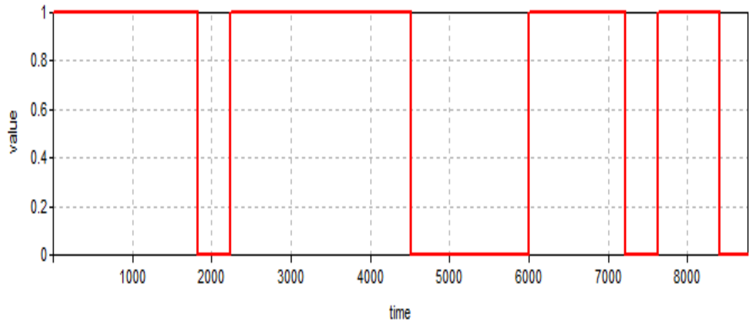
Zones	Number of Window	Orientation	Height x Width	Position[1]	Frame
			[m]	[m]	
Classrooms 1,2,3	2	West	1.50 x 2.70	1.10	Aluminum
	1	East	1.45 x 2.60	1.10	Wood
	1	East	1.75 x 1.60	1.10	Wood
Classrooms 4,5,6	2	West	1.60 x 1.60	1.10	Wood
	2	East	1.60 x 1.60	1.10	Wood
Restaurant	2	North	1.50 x 1.95	1.10	Wood
	4	South	0.95 x 1.85	2.25	Aluminum
Director Office	1	North	1.40 x 1.10	1.10	Wood
Library	1	North	1.10 x 0.70	1.10	Wood
Stored	1	East	1.35 x 1.20	1.10	Wood
Restrooms	10	North	0.45 x 0.45	2.20	Wood
Doors	-	-	0.9 x 2.1	-	Wood

[1] *Position refers to the window height from the ground level.*

The operational data for the studied primary school and calendar of entry, exit and school holidays are illustrated in Tables 4-9 and 4-10.

Table 4-9 The operational data

Parameter	Value	Unit
Internal Weather Data		
Infiltration	0.6	[ACH]
Temperature Set Range [1]	Winter 20.3-24.3	[°C]
	Summer 24.3-26.7	
Heating Set Point	20.3	[°C]
Cooling Set Point	26.7	[°C]
Occupant's Data		
Number of People	25	Person/Zone

Activity	Seated- Light Work	--
Heat Gain by Person	120	W
Clothing Factor	0.6	Clo
Metabolic Rate	1.2	Met
Control Schedule		
Daily		
Weekly		
Yearly		

[1]*Comfort temperature range selected according to ASHRAE criteria [313,314]*

Table 4-10 Calendar of entry, exit and school holidays

School entry	07/09/2021	
Autumn vacation	28/10/2021	14/11/2021
Winter vacation	16/12/2021	02/01/2022
Spring vacation	17/03/2022	03/04/2022
Summer vacation	07/07/2022	

4.4 Thermal comfort limits of the study region

Of the several thermal standards that apply to buildings, the adaptable model offers greater flexibility in aligning indoor comfort temperatures with the external climate. This is particularly beneficial for naturally ventilated structures, like the primary school examined in this case study. Research suggests that individuals living in buildings with natural ventilation may have the ability to tolerate a significantly wider range of temperatures due to behavioral and psychological adaptation [315-317]. Hence, the adaptive criteria are seen as more appropriate for fostering comfort in low-energy buildings [316,318-321].

The ASHRAE 55-2010 standard for comfort temperature [322], mandates a temperature range that must be consistently implemented across all areas and throughout the duration. This standard is universally applicable to all building types and climate zones due to the meteorological data from the RP-884 database, which originates from four continents with diverse climate zones [323]. Regrettably, the database does not have any climatic data pertaining to Africa. The ASHRAE Standard was utilized in our case study:

$$T_c = 0.31 \times T_0 + 17.8 \quad (3)$$

where T_c is the optimal temperature for comfort, and T_0 is the monthly mean outdoor temperatures.

$$T_{accept} = 0.31 \times T_0 + 17.8 \pm T_{\lim} \quad (4)$$

where T_{accept} gives the limits of the acceptable zones and $T_{\lim}$ is the range of acceptable temperatures (for 80% or for 90% of the occupants being satisfied). The given limits are $T_{\lim}$ (80%) = 3.5 °C and $T_{\lim}$ (90%) = 2.5 °C [317,320].

By employing the ASHRAE calculation, the seasonal average comfort temperatures for the examined area are determined to be 22.24°C during winter and 25.98°C during summer. The acceptance rate of 80% allows for an expansion of the comfort zones by +/- 3.5 °C. This leads to a monthly adaptive comfort range of 18.65°C (in January) to 29.86°C (in August) over the yearly cycle. The monthly comfort range, which accommodates 90% of individuals, spans from 19.65°C (in January) to 28.86°C (in August) above the average yearly temperature. The comfort zones are extended by +/- 2.5 °C.

Considering these ranges, it is justifiable to dismiss them, as the lower limits are far below the lowest average outdoor temperature in July, as shown in Figure 4-7.

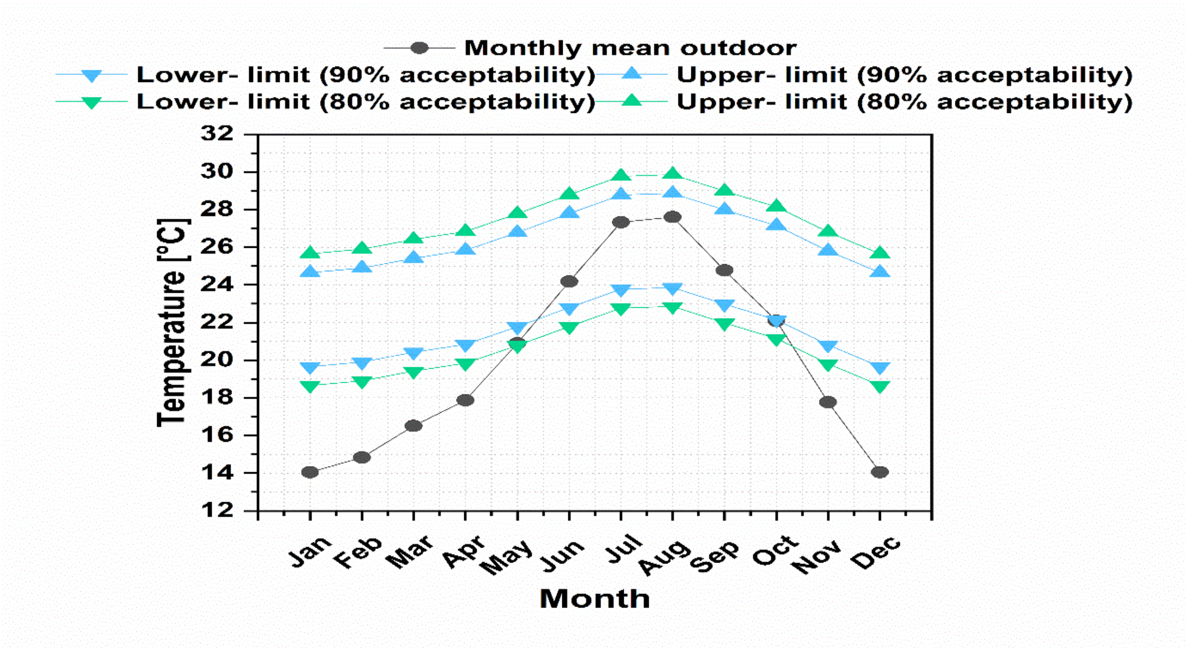


Figure 4-7 The monthly variation in the comfort temperature limits according to the ASHRAE 55-2010 standard

The monthly comfort temperature, T_c, is calculated in accordance with European Standard EN 15251 [315,320] as follows in relation to the average temperature, T_0:

$$T_c = 0.33 \times T_0 + 18.8 \qquad (5)$$

Considering an acceptable, moderate level of expectation for existing buildings, the comfort zones may be extended by +/- 4 K [315].

Based on The European standard, the average comfortable temperatures for the examined region are 23.79°C in winter and 27.57°C in summer. The adaptive monthly range varies from 19.44°C in January to 31.91°C in August, which exceeds the annual cycle.

In comparison to the ASHRAE standard, the European standard encompasses a wider scope, as outlined in Table 4-11; This table provides the average monthly comfort temperatures for the analyzed region, with a thermal acceptance range of 80% and 90% based on the ASHRAE standard, as well as the lower and upper boundaries specified by the European standard.

Table 4-11 The monthly mean comfort temperatures and limits, according to the ASHRAE 55-2010 standard and the European standard EN 15251

		ASHRAE 55-2010 Standard			European Standard EN 15251	
Month	T_0	T_c	**Lower-Upper limit (90%**	**Lower-Upper limit (80%**	T_c	**Lower-Upper limit**

	[°C]	[°C]	acceptability) [°C]	acceptability) [°C]	[°C]	[°C]
Jan	14.05	22.15	19.65-24.65	18.65-25.65	23.44	19.44-27.44
Feb	14.83	22.40	19.90-24.90	18.90-25.90	23.70	19.70-27.70
Mar	16.50	22.92	20.42-25.42	19.42-26.42	24.25	20.25-28.25
Apr	17.87	23.34	20.84-25.84	19.84-26.84	24.70	20.70-28.70
May	20.90	24.28	21.78-26.78	20.78-27.78	25.70	21.70-29.70
Jun	24.18	25.30	22.80-27.80	21.80-28.80	26.78	22.78-30.78
Jul	27.33	26.27	23.77-28.77	22.77-29.77	27.82	23.82-31.82
Aug	27.61	26.36	23.86-28.86	22.86-29.86	27.91	23.91-31.91
Sept	24.78	25.48	22.98-27.98	21.98-28.98	26.98	22.98-30.98
Oct	22.10	24.65	22.15-27.15	21.15-28.15	26.09	22.09-30.09
Nov	17.77	23.31	20.81-25.81	19.81-26.81	24.66	20.66-28.66
Dec	14.04	22.15	19.65-24.65	18.65-25.65	23.43	19.43-27.43

4.5 Methodology

The methodology presents a cohesive and comprehensive framework for evaluating passive strategies in traditional house and primary school in Ain-Temouchent, Algeria.

The methodology begins with a thorough investigation of the energy efficiency and thermal comfort of both a traditional house and a primary school in Ain-Temouchent. The focus is on identifying major deficiencies in the buildings, which are then used to provide suggestions for reducing energy consumption and improving the indoor environment through the use of passive strategies.

Subsequently, the methodology involves conducting simulations of various types of insulators with varying thicknesses for the traditional house, and examining parameters such as external shading, window-to-wall ratio (WWR), glazing types, and building envelope adjustments for the primary school. The simulations are aimed at assessing the effectiveness of the passive strategies in both buildings and determining their impact on internal thermal comfort and energy consumption.

To conduct the simulations, TRNSYS 17 software is utilized, which is a reliable tool for modeling the behavior of buildings in the Mediterranean region. The software allows for the evaluation of thermal and energy performance, aiding in the determination of optimal insulation materials, thicknesses, and glazing types for the house. In other hand, For the primary school a detailed analysis of how effective external shading devices are at different vertical shading angles, a nuanced evaluation of the best WWR to balance daylighting and heat gain or loss, a thorough examination of the thermal properties of different types of glazing, and a comprehensive study of how changes to the building envelope impact overall thermal performance.

The methodology also includes a detailed comparative analysis, aligning simulation results with the initially identified deficiencies to ensure that the suggested passive strategies are effective and contextually relevant. The goal is to generate recommendations that are tailored to improve energy efficiency and promote optimal thermal comfort in both traditional houses and primary schools.

Ultimately, the methodology aims to provide significant insights that go beyond the current situation and may be applied in various building contexts facing comparable difficulties.

Figure 4-8 illustrates the comprehensive methodology employed for evaluating passive strategies in traditional houses and primary schools in Algeria. It begins with the selection of two distinct building types: a typical Algerian house with a courtyard and thick walls, situated in Ain Temouchent, and a public school featuring a rectangular shape and flat roof. The rationale behind this selection lies in the representation of common and contrasting cases of building design and usage in Algeria, each presenting unique thermal performance and energy needs.

Moving forward, the figure details the selection of passive strategies for each building type. For traditional houses, the focus is on insulation and glazing, with four types of insulation materials and five types of glazing configurations being considered. This selection is based on the effectiveness of insulation and glazing in reducing heat transfer and enhancing thermal comfort. Conversely, for primary schools, the investigation includes external shading, window-to-wall ratio (WWR), glazing types, and building envelope adjustments. These strategies aim to improve energy efficiency and comfort by controlling solar radiation and heat gain, with factors such as shading device types and sizes being carefully chosen based on solar geometry and orientation.

The figure then outlines the parameter identification and analysis process, emphasizing the analysis of insulation thickness and glazing types for traditional houses and the evaluation of external shading, WWR, glazing configurations, and building envelope adjustments for primary schools. This step is crucial in identifying deficiencies in building performance and systematically adjusting parameters in simulation models to optimize passive strategies.

Subsequently, the research findings are presented, highlighting the effectiveness of passive strategies in both traditional houses and primary schools. Key insights and implications for building design and retrofitting are discussed, followed by a validation of simulation results against empirical data or real-world case studies to ensure accuracy and reliability. The outcomes of the research, including improvements in thermal comfort and energy efficiency achieved through passive strategies, are summarized, and a comparative analysis with recent studies and industry standards is conducted to contextualize the contributions of the study and identify areas for further investigation. Finally, optimization recommendations are provided based on research findings and comparative analysis to optimize passive strategies in traditional houses and primary schools.

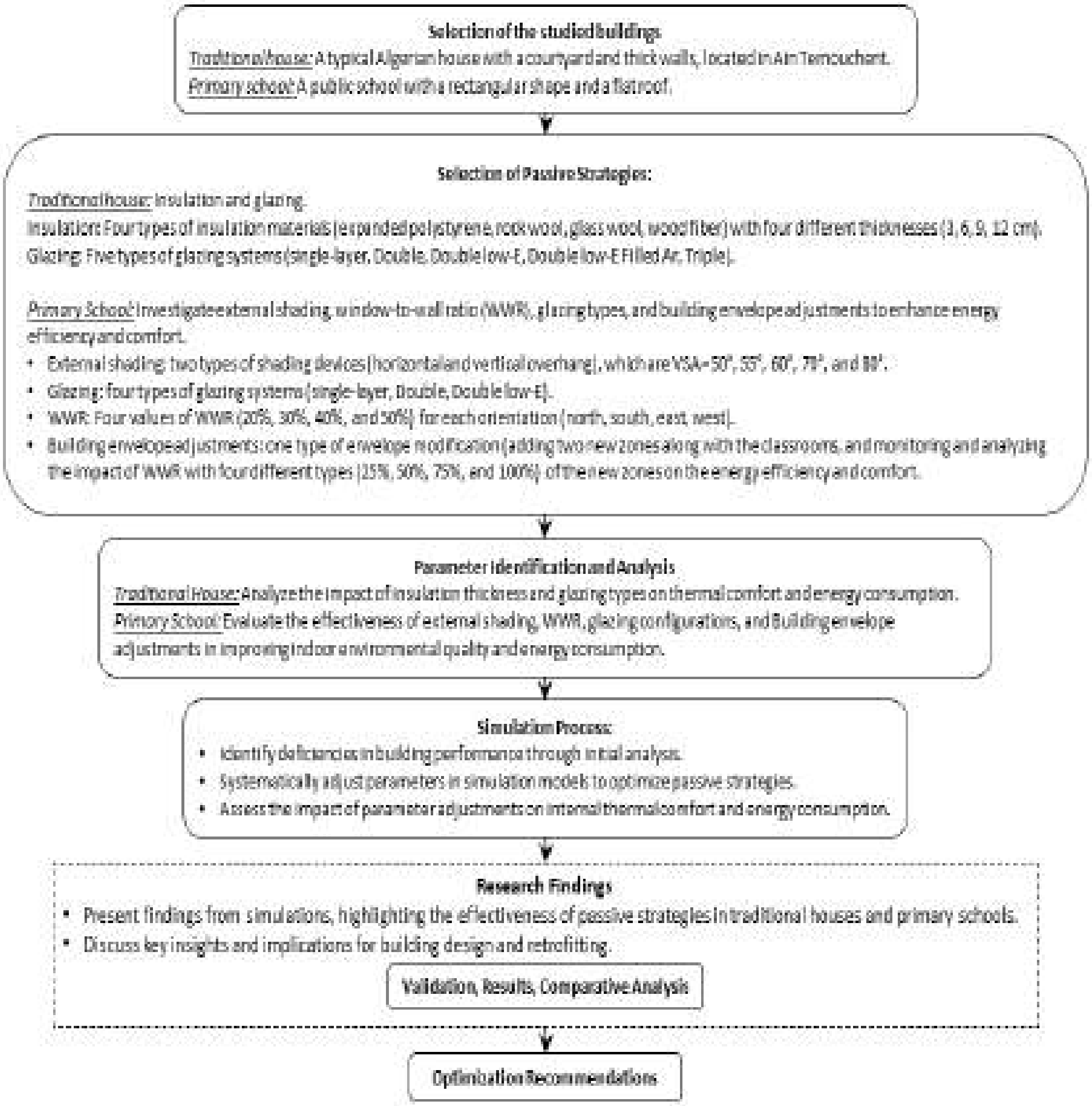


Figure 4-8 Methodological framework for evaluating passive strategies in traditional houses and primary schools in Ain Temouchent, Algeria

5 Mathematical Foundations of Simulation and Numerical Simulation

5.1 Mathematical modelling

Building modelling was done with Type-56 and TRNBuild. This component models the thermal behavior of a building divided into different thermal zones. The TRNBuild program reads in and processes a file containing the building description (the outputs and required inputs of Type 56). Type 56 is an energy balance model that will be used during a TRNSYS simulation.

5.1.1 Thermal Zone / Air node

A zone may have more than one air node. Convective heat flux to the air node calculated by the given equation:

$$\dot{Q}_i = \dot{Q}_{Surf,i} + \dot{Q}_{\inf,i} + \dot{Q}_{vent,i} + \dot{Q}_{g,c,i} + \dot{Q}_{cplg,i} + \dot{Q}_{solair,i} + \dot{Q}_{ISHCCI,i} \qquad (6)$$

Where:

$\dot{Q}_{Surf,i}$	The convective gain from surfaces.
$\dot{Q}_{\inf,i}$	The infiltration gains (airflow from outside only), given by $\dot{Q}_{\inf,i} = \dot{V}\cdot\rho\cdot c_p(T_{outside,i} - T_{air})$
$\dot{Q}_{vent,i}$	The ventilation gains (airflow from a user-defined source, like an HVAC system), given by $\dot{Q}_{vent,i} = \dot{V}\cdot\rho\cdot c_p(T_{ventilation,i} - T_{air})$
$\dot{Q}_{g,c,i}$	The internal convective gains (by people, equipment, illumination, radiators, etc.)
$\dot{Q}_{cplg,i}$	The gains due to (connective) airflow from air node i or boundary condition, given by $\dot{Q}_{cplg,i} = \dot{V}\cdot\rho\cdot c_p(T_{zone,i} - T_{air})$
$\dot{Q}_{solair,i}$	The fraction of solar radiation entering an air node through external windows is immediately transferred as a convective gain to the internal air.
$\dot{Q}_{ISHCCI,i}$	The absorbed solar radiation on all internal shading devices of the zone and directly transferred as a convective gain to the internal air.

The heat fluxes and temperatures characterize the thermal behavior of any wall or window. The walls are modelled according to the transfer function relationships of Mitalas and Arseneault [324] defined from surface to surface. A window is thermally considered as an external wall with no thermal mass, partially transparent to solar, but opaque to long-wave internal gains. Long-wave absorption is considered to occur only at the surfaces. In the energy balance calculation of Type 56, the window is described as a 2-node model. The method of the transfer function or response factors can be described as the method to tell the "thermal history" of the wall. The wall is considered a black box. A zone is restricted to a single air node. The long-wave radiation exchange between the surfaces within the air node and the convective heat flux from the inside surfaces to the air node air are approximated using the star network given by Seem [325]. This method uses an artificial temperature node T_{star} to consider the parallel energy flow from a wall surface by convection to the air node and by radiation to other wall and window elements. The total gain to air node i from all surfaces is the sum of the combined heat transfers

$$\begin{aligned}\dot{Q}_{surf,i} = \sum A_s q_{comb,i} = \sum_{j=1}^{Adj.Zones} \sum_{i=1}^{surface(i.to.j)} A_s B_s T_{star,j} + \sum^{ext.surfaces} A_s B_s T_a + \\ \sum^{int.walls} A_s B_s T_{star} + \sum^{known.bound} A_s B_s T_{b,s} + \sum^{surface.in.zone.i} A_s (C_s T_{star,i} - D_s - S_{s,i})\end{aligned} \quad (7)$$

Where

$\dot{Q}_{Surf,i}$	The convective gain from surfaces.
A_s	The inside area of surface s.
$q_{comb,i}$	Combined convective and radiative heat flux to the surface i.
B_s, C_s, and D_s	They express the inside surface heat flux for an external wall as a function of the boundary air temperatures.
T_{star}	Star node temperature of airnode.
T_a	Ambient air temperature.
$T_{b,s}$	Boundary temperature of surface s.
$S_{s,i}$	Radiation heat flux absorbed at the inside surface (solar and radiative gains).

Both sides of an internal wall are considered inside surfaces and must be included twice in Equation (7). An energy balance on the star node expressed:

$$\dot{Q}_{surf,i} = \frac{1}{R_{star,i}} (T_{star,i} - T_i) \quad (8)$$

Where

R_{star}	Resistance of the star node.

Infiltration and ventilation rates are given in terms of air changes per hour for each air node. The mass flow rate is the product of the air node air volume, air density, and air change rate. Infiltration occurs always from outdoor conditions, while ventilation occurs from a specified (possibly variable) temperature. Equal amounts of air are assumed to leave the air node at the air node temperature. The energy gains to any air node i due to infiltration and ventilation are:

$$\dot{Q}_{\inf,i} = \dot{m}_{\inf,i} \cdot c_p (T_a - T_i)$$
$$\dot{Q}_{vent,i} = \sum_{k}^{n.vent} \dot{m}_{v,k,i} \cdot c_p (T_{v,k} - T_i) \qquad (9)$$

Where:

$\dot{m}_{\inf,i}$	Mass flow rate of infiltration air.
$\dot{m}_{v,k,i}$	Mass flow rate of ventilation air of ventilation type k.
c_p	Specific heat of the air.
$T_{v,k}$	Temperature of ventilation air of ventilation type k.
T_a	Ambient air temperature.

For each wall or window separating air nodes of floating temperature or each wall having a known boundary condition, it is possible to specify a convective coupling. This coupling is the mass flow rate that enters the air node across the surface. An equal quantity of air is assumed to leave the air node at the air node temperature. The energy gains due to the convective coupling are the sum of all such gains for all walls or windows in the air node.

$$\dot{Q}_{cp\lg,i} = \sum^{Adj.zones} \sum^{surface(i.to.j)} \dot{m}_{cp\lg,s}\, c_p (T_j - T_i) + \cdots + \sum^{known.bound} \dot{m}_{cp\lg,s}\, c_p (T_{b,s} - T_i) \qquad (10)$$

Where $\dot{m}_{cp\lg,s}$ is the mass flow rate of air entering air node i across walls or windows.

The distribution of solar radiation a so-called solar to air factor which is used in several standards is integrated. The solar to air factor $f_{solair,i}$ defines the fraction of solar radiation entering an air node through external windows which is immediately transferred as a convective gain to the internal air.

$$\dot{Q}_{solair,i} = f_{solair,i} \cdot (I_{trans,dif,i} + I_{trans,dir,i}) \qquad (11)$$

Where:

$\dot{Q}_{solair,i}$	Solar radiation enters the air node through external windows which are immediately transferred as a radiative gain to the air node i.
$f_{solair,i}$	Is the solar to air fraction to the air node i.
$I_{trans,dif,i}$	Is the diffuse solar radiation transmitted through all external windows of the air node i.
$I_{trans,dir,i}$	Is the direct solar radiation transmitted through all external windows of the air node i.

The rate of change of internal energy for any free-floating air node is equal to the net heat gain

$$C_i \frac{d}{dt} T_i = \dot{Q}_i \qquad (12)$$

where C_i is the thermal capacitance of air node i (minimal = $V_i \times r \times c_p$ with V_i = air node volume).

The net heat gain, $\dot{Q}_i$, is a function of T_i the temperatures of all other air nodes adjacent to air node i. To simplify the solution of the set of equations $\dot{Q}_i$ is considered constant during any timestep, evaluated at average values of the air node temperatures. In this case, the solution to the differential equation for final temperature for a given time interval is

$$T_{i,t} = T_{i,t-\Delta t} + \frac{\overline{\dot{Q}_{i\Delta t}}}{C_i} \tag{13}$$

Where:

Δt	The simulation time-step.
$T_{i,\tau-\Delta t}$	The air node temperature at the beginning of the time-step.

The temperature variation is linear, such that the average is:

$$T_i = \frac{T_{i,t} + T_{i,t-\Delta t}}{2} \tag{14}$$

If Equation (14) is solved for $T_{i,\tau}$ and the result substituted into Equation (13), along with the individual expressions representing the net heat gain, the following is obtained:

$$\begin{aligned}\frac{2\cdot Ci\cdot(\overline{T}_i - T_{i,\tau-\Delta t})}{\Delta t} &= \sum_{j=1}^{Adj.zones}\sum^{surface(i.to.j)}\left(\dot{m}_{cp\lg,s}c_p\overline{T}_j + \dot{\mathrm{m}}_{\inf,i}\cdot c_p\cdot T_a\right) + \sum^{known.boundaries}\dot{m}_{cp\lg,i}\cdot c_p\cdot T_{b,s} - \\ &\left(\frac{1}{R_{star,i}} + \left(\sum^{known.boundaries}\dot{m}_{cp\lg,i} + \sum_{j=1}^{Adj.zones}\dot{m}_{cp\lg,s} + \dot{\mathrm{m}}_{\inf,i} + \sum_{k}^{n.vent}\dot{\mathrm{m}}_{v,k,i}\right)c_p\right)\overline{T_i} \\ &+\left(\frac{1}{R_{star,i}}\cdot\overline{T_{star,i}} + \sum_{k}^{n.vent}\dot{\mathrm{m}}_{v,k,i}\cdot c_p\cdot T_{v,k} + Q_{g,c,i}\right)\end{aligned} \tag{15}$$

Equations (7) and (8) can be equated and regrouped to find:

$$\begin{aligned}&\left(\frac{1}{R_{star,i}} - \sum^{\mathrm{int}.walls}A_sB_s + \sum^{surf.ini}A_sC_c\right)\overline{T_{star,i}} - \left(\sum^{Adj.Zones}\sum^{walls(i.to.j)}A_sB_s\right)\overline{T_{star,j}} - \frac{1}{R_{star,i}}\overline{T_i} = \\ &\left(\sum^{ext.surfaces}A_sB_s\right)T_a + \sum^{known.boundaries}A_sB_sT_{b,s} + \sum^{surface.in.zone.i}A_s(D_s + S_{s,i})\end{aligned} \tag{16}$$

The set of energy balances given by Equations (15) and (16), written for all air nodes, results in a linear set of equations in average air node temperatures and average star temperatures. In matrix form,

$$[X][\overline{T}]=[Z] \qquad \textit{This matrix can be partitioned such that}$$
$$[X]=\begin{bmatrix} X_{11} & X_{12} \\ X_{21} & X_{22} \end{bmatrix}$$
$$[T]=\begin{bmatrix} \overline{T_1} \\ \overline{T_2} \end{bmatrix}=\begin{bmatrix} \overline{T} \\ \overline{T_{star}} \end{bmatrix} \tag{17}$$
$$[Z]=\begin{bmatrix} Z_1 \\ Z_2 \end{bmatrix}$$

Where:

$$X_{11,ii}=\left(\sum^{surface(i.to.j)}\dot{m}_{cp\lg,s}+\dot{\mathrm{m}}_{\inf,i}+\sum_{k}^{n.vent}\dot{\mathrm{m}}_{v,k,i}\right)\cdot c_p+\frac{2\cdot Ci}{\Delta t}+\frac{1}{R_{star,i}}+\sum^{known.boundaries}\dot{m}_{cp\lg,i}\cdot c_p$$

$$X_{11,ij}=-\left(\sum_{j=1}^{Adj.zones}\sum^{surface(i.to.j)}\dot{m}_{cp\lg,s}\cdot c_p\right) \qquad \text{for } i\neq j$$

$$X_{12,ii}=-\frac{1}{R_{star,i}}$$

$$X_{12,ij}=0 \qquad \text{for } i\neq j$$

$$X_{21,ii}=-\frac{1}{R_{star,i}}$$

$$X_{21,ij}=0$$

$$X_{22,ii}=\left(\frac{1}{R_{star,i}}+\sum^{\text{int}.walls}A_sB_s+\sum^{surf.in.zone.i}A_sC_s\right)$$

$$X_{22,ij}=-\left(\sum^{Adj.Zones}\sum^{walls(i.to.j)}A_sB_s\right)$$

$$Z_{1,i}=\dot{\mathrm{m}}_{\inf,i}\cdot c_p\cdot T_a+\sum^{known.boundaries}\dot{m}_{cp\lg,i}\cdot c_p\cdot T_{b,s}+\sum_{k}^{n.vent}\dot{\mathrm{m}}_{v,k,i}\cdot c_p\cdot T_{v,k}+\frac{2\cdot Ci\cdot T_{i,\tau-\Delta t}}{\Delta t}+Q_{g,c,i}$$

$$Z_{2,i}=\left(\sum^{ext.surfaces}A_sB_s\right)T_a+\sum^{known.boundaries}A_sB_sT_{b,s}+\sum^{surface.in.zone.i}A_s(D_s+S_{s,i})$$

For the case of all air nodes in floating temperature,

$$[\overline{T}]=[X]^{-1}[Z] \tag{18}$$

The final temperature for each air node i is

$$\mathrm{T}_{i,\tau}=2\overline{\mathrm{T}}_i-\mathrm{T}_{i,\tau\text{-}\Delta t} \tag{19}$$

The energy requirements for heating and cooling are determined based on air nodes controlled in an idealized manner. Therefore, the heating and cooling energy flow is

directly connected to the air node air temperature node. The output of the heating and/or cooling equipment is a function of the air node temperature as shown in Figure 5-1.
Where:

P_i	Power output for air node I (negative for heating, positive for cooling).
$P_{\max,i}$	Absolute value of the maximum power for air node i.
$T_{set,i}$	Set temperatures for heating or cooling in air node i.

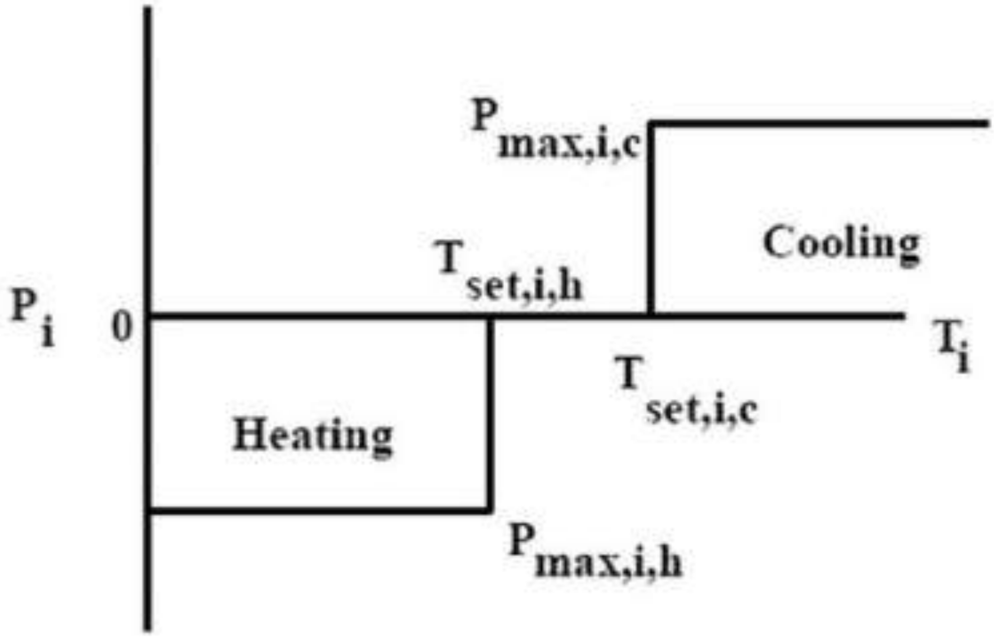


Figure 5-1 Power output versus temperature [310]

For the simulation of heating equipment that produces a partially radiative gain to the air node, the radiative fraction of the supplied heating power may be defined. This fraction of the power is supplied as internal radiative gains and distributed to the walls of the air node. As the set temperature for the heating equipment is related to the air temperature of the air node, the radiative fraction of the heating power cannot be higher than 0.99 in order to have a convective part left to ensure stable control of the heating equipment.
The air node temperature is free-floating in the comfort region where the power is zero. If the temperature of a free-floating air node is within the heating or cooling regions at the end of a timestep, power is applied throughout the timestep so that the final air node temperature just reaches T_{set}. If the power required is greater than the maximum specified, then the maximum power is applied throughout the timestep and the air node temperature is again free-floating.
The temperature change of the air node air, when power is supplied, is assumed to be linear. If power is required and enough is available to maintain the final air node

temperature $T_{set,i}$, then the final and average air node temperatures are known.

$$T_t = T_{set,i}$$
$$T_{req,i} = \frac{T_{\tau-\Delta t} + T_{set,i}}{2} \tag{20}$$

Where $T_{req,i}$, is the average air node temperature over the time-step if less than maximum power is required.

It is necessary to consider the general case of air nodes that are in different control regions. With the inclusion of the control laws, the equations remain linear. For the air nodes that have floating temperatures, the solution for average air node temperatures and star temperatures is again of the form.

$$\left[\overline{T}\right] = \left[X^{'}\right]^{-1}\left[Z^{'}\right] \tag{21}$$

The coefficients of the $X^{'}$ matrix and $Z^{'}$ vector depend upon the control region. In the comfort air node, with no energy requirement:

$$X^{'}_{ij} = X_{ij} \qquad \text{for all i and j.}$$
$$Z^{'}_{i} = Z_i \tag{22}$$

For air nodes whose temperature falls below the point for maximum heating or above that for maximum cooling.

$$X^{'}_{ij} = X_{ij} \qquad \text{for all i and j.}$$
$$Z^{'}_{i} = Z_i + P_{\max,i,h} Z\_i^{\wedge'} = Z_i - P\_(\max, i, c) \tag{23}$$

For air nodes that fall within the heating or cooling regions and require less than maximum power, the final temperature is assumed to be equal to the heating or cooling set temperature and the average room temperature is then, $T_{req,i}$. Equation (12) can be rewritten to include the power requirements.

$$Ci\frac{d}{dt}T_i = \dot{Q}_i - P_i \tag{24}$$

P_i and $\dot{Q}_i$ are considered constant over the time-step and $\dot{Q}_i$ is evaluated at the average air node temperature. Substituting into Equation (19) yields:

$$
\begin{aligned}
& P_i - \frac{1}{R_{star,i}} \cdot T_{star,i} - \sum_{j=1}^{Adj.zones} \sum^{surface(i.to.j)} \dot{m}_{cp\lg} c_p \overline{T}_j = \\
& = -\left[\frac{1}{R_{star,i}} + \begin{pmatrix} \dot{\mathrm{m}}_{\inf,i} + \sum_k^{m.vent} \dot{\mathrm{m}}_{v,k,i} + \\ \sum_{j=1}^{Adj.zones} \sum^{surface(i.to.j)} \dot{m}_{cp\lg} + \sum^{known.boundaries} \dot{m}_{cp\lg,} \end{pmatrix} c_p \right] \overline{T_{req,i}} \\
& - \frac{Ci}{\Delta t}(T_{set,i} - T_{i,\tau-\Delta t}) + \dot{\mathrm{m}}_{\inf,i} \cdot c_p \cdot T_a \cdot \sum^{n.vent} \dot{\mathrm{m}}_{v,k,i} \cdot c_p \cdot T_{v,k} + Q_{g,c,i} \\
& + \sum^{known.boundaries} \dot{m}_{cp\lg,s} \cdot c_p \cdot T_{b,s}
\end{aligned}
\tag{25}
$$

Equation (25) is substituted into the set of energy balances on all air nodes for any air node that is in the less than maximum heating or cooling region. The solution given by Equation (21) is valid with the following substitutions for air nodes evaluated with Equation (25).

$X'_{11,ij} = X_{11,ij}$ for $i \neq j$

$X'_{11,ii} = 1.0$

$X'_{12,ij} = X_{12,ij}$

$X'_{22,ii} = X_{22,ii}$

Equation (16) is corrected by adding $\left(\frac{1}{R_{star,i}} T_{req,i} \right)$ to both sides of the equation, then

$X'_{21,ii} = 0$

$Z'_{2,1} = Z_{2,i} - X_{11,ii} T_{req,i}$

For any air node i connected to any air node m at a fixed set-point, the X' matrix and the Z' vector are modified as

$X'_{11,im} = 0$

$Z'_i = Z'_i - X'_{im} T_{req,m}$

The solution is given by Equation (21) using the adjusted matrix entries is valid with one further note. The temperature vector contains the required power instead of the average air node temperature, for those air nodes in the less than heating or cooling regions.

In order to determine the proper control regions for all air nodes, temperatures are calculated for the case of no heating or cooling. This allows a first estimate of the control. For air nodes where heating or cooling is required, the energy required to maintain the final air node temperature at the set temperature is determined. If the required energy is less than the maximum power available, then the air node is considered to be within the less than maximum heating or cooling region. Otherwise, the heating or cooling output is equal to the maximum. Elements of the $X^{'}$ matrix and $Z^{'}$ vector are set according to the control situation. The system of equations represented by the matrix Equation (21) is solved. This process is repeated until the control is not changing. The energy requirements are then evaluated for the air nodes maintained at fixed setpoints.

5.1.2 Thermal Window Model

A complex fenestration model has been incorporated into the Type 56 component using output data from the WINDOW 4.1 program developed by Lawrence Berkeley Laboratory, USA [326]. Windows may consist of more than a glazing pane with different gas fillings between them. For each glazing of the window, the resulting temperature is calculated considering transmission, absorption and reflection of incoming direct and diffuse solar radiation, diffuse short-wave radiation being reflected from the walls of the air node or an internal shading device, convective, conductive and long-wave radiative heat transfer between the individual panes and with the inner and outer environment.

Total energy flux through the window glazing is calculated after having determined the individual pane temperatures and all of the heat fluxes through the glazing's, the absorbed short-wave radiation is summed over the various window panes and distributed to the inner and outer window nodes. Based on the temperatures of the window nodes, the absorbed short-wave radiation of the window nodes is found to be

$$\begin{aligned} \dot{Q}_{abs,i} &= 0.5(\dot{Q}_{abs} + h_i(T_i - T_{zone}) - h_o(T_o - T_{amb}) - \dot{Q}_{sky}) \\ \dot{Q}_{abs,a} &= \dot{Q}_{abs} - \dot{Q}_{abs,i} \end{aligned} \tag{26}$$

Where:

$\dot{Q}_{abs}$	The absorption of short-wave radiation (direct and diffuse solar radiation, diffuse reflected radiation from the all the surfaces of the airnode and the optional inner shading device) on the glazing system of the window leads to a heat flux from the pane to the airnode.
$\dot{Q}_{sky}$	Longwave rad. losses to sky of external surface
h_i	The heat transfer coefficients
h_o	The solar absorptance is used for both sides of the frame

These heat fluxes of the two-node model are used in the Type 56 heat balance algorithm to calculate the dynamic behavior of the multi-air node building.

Edge correction coefficients are calculated by the WINDOW 4.1 program [326]. These correction coefficients and the height and width of a glazing sample defined in the TRNBuild program and the U-value of the glazing is calculated as a shunt circuit of the center of glass value, U_{center} and the U-value of the glazing edge, U_{edge}:

$$\mu_{edge} = c_{edge,1} + c_{edge,2}\mu_{center} + c_{edge,3}\mu^{2}_{center} \tag{27}$$

In the building description, the ratio of the frame area to the total window area is defined. Additionally, a U-value for the frame is given there. The total U-value of the window is calculated as the arithmetic mean value of glazing and frame U-value:

$$\mu_{window} = f_{frame}\mu_{frame} + (1 - f_{frame})\mu_{glass} \tag{28}$$

In the heat balance algorithm of Type 56, all the heat flows and the resulting temperatures are related to the total window area.

5.1.3 External and Internal Shading Devices

External or internal shading devices may be defined for each external window of the building. In TRNSYS (Version 17.1) an integrated radiation depending control of the shading devices for external windows is available.

5.1.3.1 External shading

External shading devices reduce the incoming solar radiation on the glazing area of the extern window by a factor given in the building description. A thermal resistance that reduces the heat losses of the glazing to the ambient, if the external shading device is active, it may be specified.

5.1.3.2 Internal shading

For internal windows only an internal shading device for the surface defined as FRONT in the building description may be defined.

An internal shading device is specified giving the reduction of the transmitted solar radiation, a reflection coefficient for solar radiation for both faces of the shading device and a parameter defining the degree of additional convection to the air node. The model takes into account multiple reflections between the internal shading device and the window panes and calculates the absorption of reflected solar radiation from the internal shading on the different window panes. The multiple reflections between internal shading and window panes can be expanded into a endless series and expressed in a closed form for each face of the window resulting in

$$\dot{q}_{\text{int},sh} = \left[f_{\text{int},sh}(1-refl_{sh,o}) + (1-f_{\text{int},sh})\left(\frac{refl_{win,i}\, f_{\text{int},sh}(1-refl_{sh,i})}{1-refl_{win,i}\, f_{\text{int},sh} refl_{sh,i}}\right)\right] I_{ref,z}$$
$$+trans_{win}\left(\frac{f_{\text{int},sh}(1-refl_{sh,i})}{1-refl_{win,i}\, f_{\text{int},sh} refl_{sh,i}}\right) I \qquad (29)$$

Where:

$f_{\text{int},sh}$	Non transparent fraction of internal shading related to the total glass area
$refl_{sh,i}$	solar reflection of internal shading facing the glass
$refl_{sh,o}$	solar reflection of internal shading facing the room
$refl_{win,i}$	solar reflection of glass surface facing the internal shading device
$trans_{win}$	solar transmittance of all window panes

This calculation is performed separately with the optical properties for direct and diffuse solar radiation and the total absorption of the internal shading device is given by the sum of absorption of direct and diffuse solar radiation parts.

With the internal shading device located behind the inner glazing an additional convection is started resulting in a chimney effect of warm air heated by the absorption of solar radiation on the shading device. The absorbed solar radiation on the inner shading is given as the product of the transmitted solar radiation and the fraction of the shaded glazing area considering the reflected radiation and the fraction which is transferred to the air node of the air node via the specified additional convection:

$$\dot{q}_{abs,sh} = \dot{q}_{\text{int},sh}(1-c_{conv,sh}) \qquad (30)$$

The additional convective heat flow to the air node of the air node is therefore given as:

$$\dot{q}_{conv,sh} = \dot{q}_{\text{int},sh} c_{conv,sh} \qquad (31)$$

5.2 A Step-by-Step Guide to Using Meteonorm, Climate Consultant, SketchUp, and TRNSYS for Building Energy Simulation

This section offers a comprehensive guide on utilizing software tools to evaluate building energy performance. It begins by detailing the process of extracting and accessing meteorological data and visualizing climate patterns using Meteonorm and Climate Consultant. Subsequently, it provides detailed instructions on creating intricate 3D models with SketchUp, followed by essential inputs required to conduct energy simulations using TRNSYS. By offering a step-by-step approach, this guide ensures users possess the necessary knowledge and techniques to effectively harness these software tools for thorough building energy analysis. More information on the guide to using Meteonorm, Climate Consultant, SketchUp, and TRNSYS for building energy simulation can be found in Appendix II.

5.3 Case Study Presentation

5.3.1 Traditional house

Figure 5-2 depicts the detailed architectural design for the studied house, which has been built on an area of 85m^2 with a height of 4m. The house is designed to provide comfortable living spaces and includes two bedrooms, a bathroom, a living room, a dining room, a kitchen that is attached to a courtyard, and a guest room. To ensure optimal functionality and maximum utilization of space, the building has been meticulously divided into nine zones. The careful consideration of these zones allows for efficient management of the different areas of the house and enhances the overall flow and functionality of the living space.

The architectural design of the house was created using SketchUp design software and the TRNSYS 3D Plugin tool. These software tools allow for detailed and accurate 3D modelling and simulation, enabling designers to create a realistic and comprehensive visual representation of the building. Overall, the architectural design of this house aims to provide a functional, comfortable, and aesthetically pleasing living space for its inhabitants.

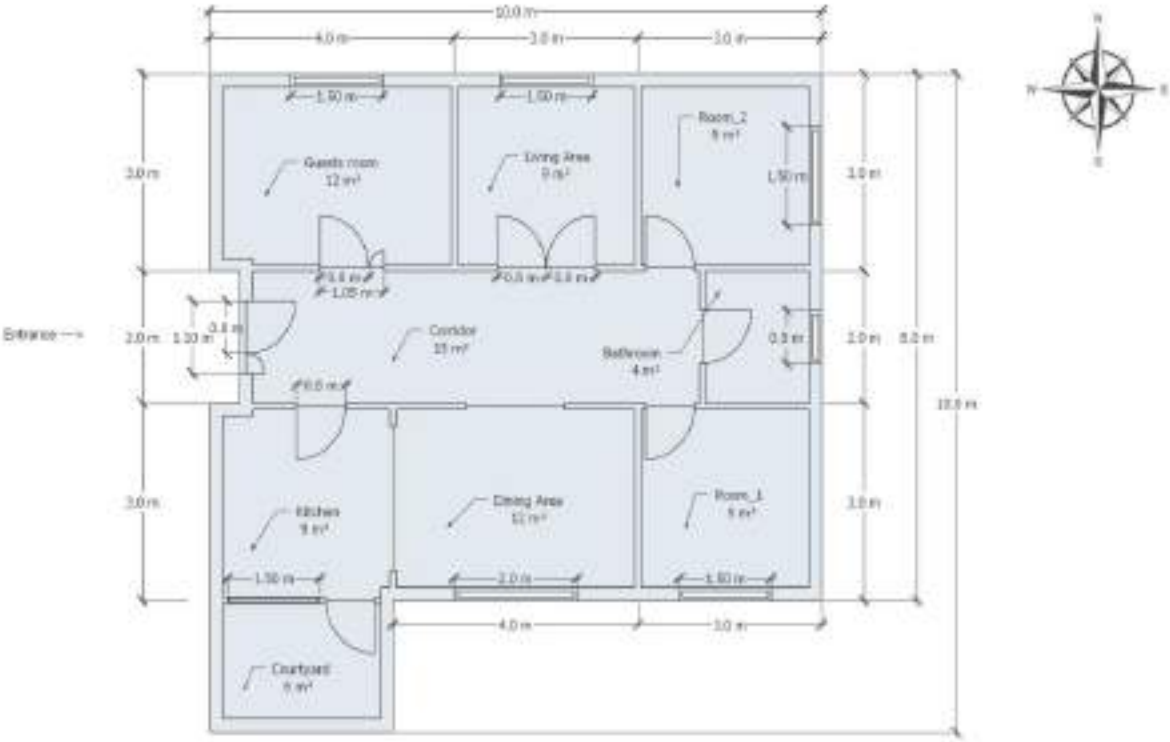


Figure 5-2 House architectural design

5.3.1.1 Hypotheses

- ❖ The investigated house has four outside facades, and the roof is exposed to outside;
- ❖ The thermophysical properties of the materials used are obtained entirely from the TRNSYS 17 library and used research papers in the literature review;
- ❖ Meteorological data of the city of Ain Temouchent was provided from the Meteonorm program [307];
- ❖ The infiltration rate is calculated via the computed empirical relation used in various research publications. the infiltration rate equation is

$$Infiltration = 0.07 \cdot V_{Wind} + 0.4 \qquad \text{[ACH]} \qquad (32)$$

Where

V_{Wind} expresses the wind velocity [m/s];

[ACH]: Air Changes per Hour.

- ❖ The temperature of the soil is obtained from the Ain Temouchent meteorological file generated from the Meteonorm program [307];
- ❖ The internal gains (Equipment, Lights and People) are zero (unoccupied house);
- ❖ Thermal bridges are not taken into account;
- ❖ The simulation time step is one hour.

5.3.2 Primary school

The primary school is located in the center of the village, as shown in the Figure 5-3. It has four facades, all overlooking the road. It is bordered on the north by houses, on the north-east, a small forest with a football field, on the south-east is a mosque, on the south are houses, and on the east are a water pump and houses. The houses and facilities do not offer any obstruction of solar radiation to the school all year.

Figure 5-3 Location of Rezigui Boussif primary school, Khoualed Abdel Hakem, Ain Temouchent Wilaya [327]

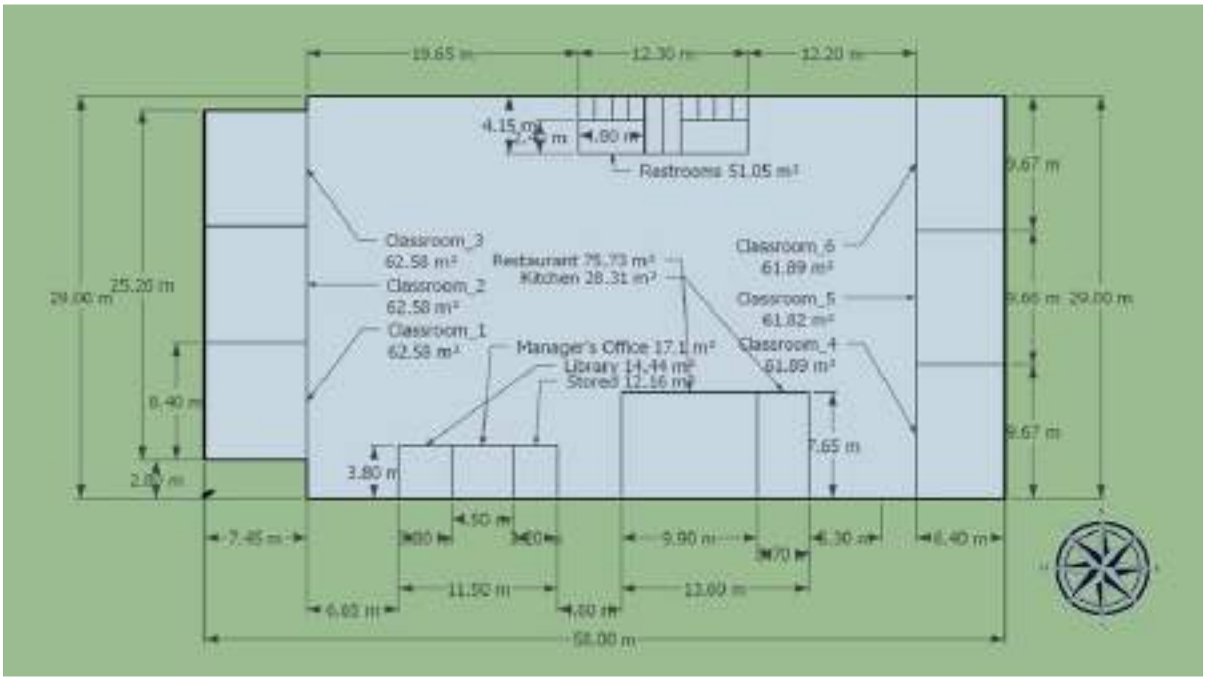


Figure 5-4 Facilities scheme of Rezigui Boussif primary school, Khoualed Abdel Hakem, Ain Temouchent Wilaya

This primary school was opened in December 1986. It was built on an area of 1653.69 m^2 as shown in Table 5-1. The school contains the following facilities: There are a total of six classrooms; three on the eastern side and three on the western side. On the south side are located Director's Office, Stored, Library, Kitchen and Restaurant. On the north side, we find the restrooms. as illustrated in Figure 5-4. The dimensions of the facilities are depicted in the Table 5-2. Figure 5-5 presents a compelling collection of photographs showcasing the primary school studied.

Table 5-1 Additional information about the primary school

Country	Algeria	**Primary school name**	Rezigui Boussif
Wilaya	Ain Temouchent	**Completion date**	1986
Municipality	Sidi Ben Adda	**Opening date**	December 1986
Village	khoualed Abdel Hakem	**Total area**	1653.69 m^2
Latitude	35.3590° N	**Built-up area**	572.125 m^2
Longitude	1.2743° W	**Location**	Rural
Altitude	76 m		
Address	Al Hilal Beach Sidi Ben Adda		

Figure 5-5 Photographs of the studied primary school

Table 5-2 The school facilities' dimensions

Item	Dimensions	Area
	(Length × Width × Height)	(Length × Width)
	[m]	[m^2]
Classroom West Side (3)	8.40 × 7.45 × 4.0	62.58
Classroom East Side (3)	9.67 × 6.40 × 4.0	61.89
Director Office	4.50 × 3.80 × 4.0	17.10
Library	3.80 × 3.80 × 4.0	14.44
Kitchen	3.70 × 7.65 × 4.0	28.31
Restaurant	9.90 × 7.65 × 4.0	75.74
Stored	3.20 × 3.80 × 4.0	12.16
Restrooms	12.30 × 4.15 × 4.0	51.05

6 Results and Discussions

This chapter presents the culmination of two comprehensive research endeavors focusing on the energy performance of buildings in the Mediterranean region, specifically traditional house and primary school. Drawing from rigorous investigations and simulations, the findings outlined herein offer valuable insights into strategies for enhancing energy efficiency and thermal comfort in architectural settings. The first research paper [328], examines the impact of insulation materials and window glazing on energy consumption and indoor thermal conditions in traditional house, revealing significant reductions in energy costs and improvements in thermal comfort through optimal insulation and glazing configurations. Meanwhile, the second research paper [329] delves into the thermal dynamics of primary school classrooms, emphasizing the efficacy of passive design strategies such as shading devices, Window-to-Wall Ratio (WWR) adjustments, and advanced glazing types in achieving substantial energy savings and maintaining indoor comfort. By synthesizing empirical data with theoretical insights, this chapter elucidates key factors influencing building energy performance and provides actionable recommendations for architects, engineers, and policymakers seeking to promote energy-conscious practices and sustainable building design in Mediterranean climates.

6.1 Traditional house

To conduct the simulation, TRNSYS 17 simulation program was used. The house was divided into nine zones, with the courtyard zone assumed to be a shaded group during the architectural design modelling process in SketchUp software using the TRNSYS 3D-Plugin. As shown in Figure 6-1.

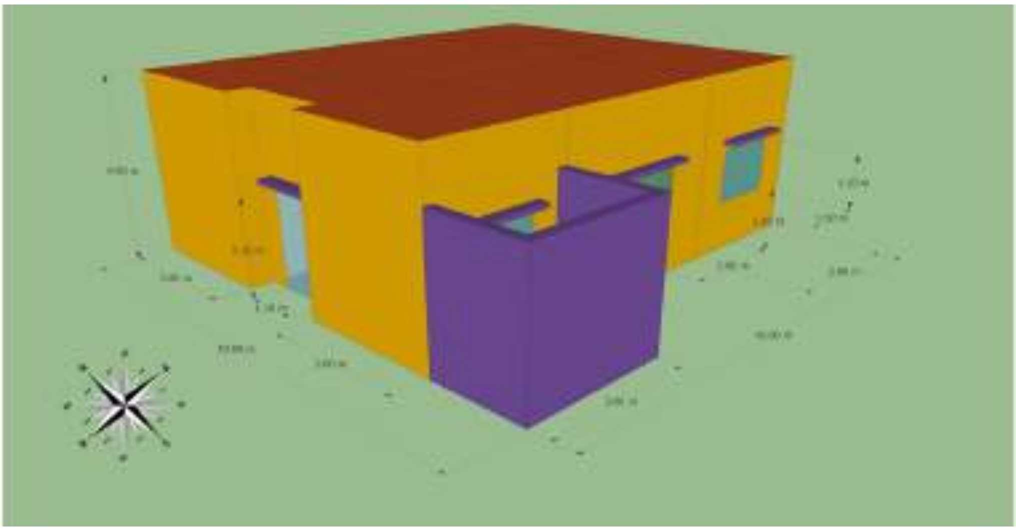


Figure 6-1 A 3D schematic for the studied house

Figure 6-2 displays the yearly ambient temperature variations in Ain Temouchent. The ASHRAE Standard-55 criteria [313] divides the temperature readings into two comfort zones for winter and summer, illustrated in Figure 6-2. The range for winter comfort is 20.3-24.3°C, while that for summer is 24.3-26.7°C. Winter comfort spans December 21 to June 21, which encompasses the winter and spring seasons, while summer comfort ranges from June 21 to December 21, comprising summer and fall seasons. Within a year, 30% of the hours achieved thermal comfort, which amounts to 590 hours for winter and 744 hours for summer. These results provide valuable insights into the amount of time during which residents could expect to experience comfortable indoor temperatures in Ain Temouchent.

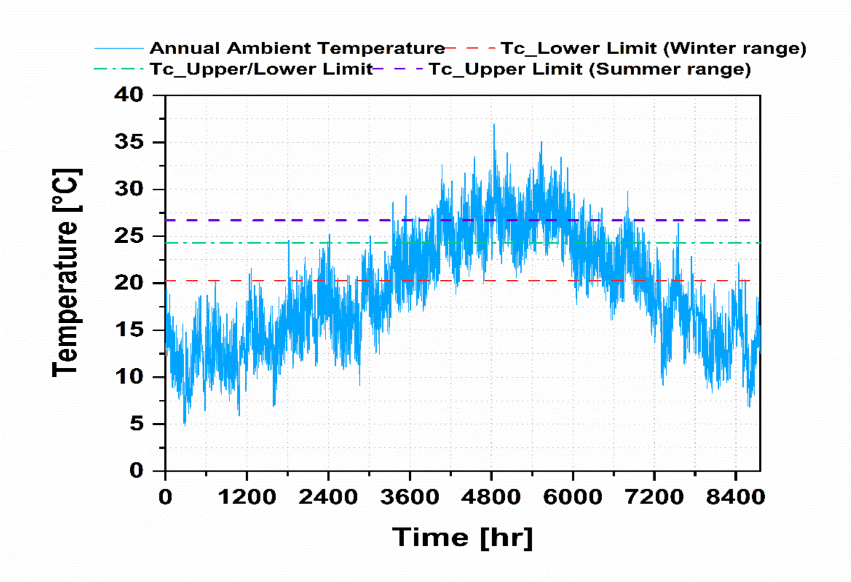


Figure 6-2 Temperature evolution of the city of Ain Temouchent over a year

6.1.1 The effect of insulators of varied thicknesses on the indoor environment and energy consumption

The simulation was carried out assuming that the window design contains a single pane of glass, as shown in the glass type in Table 4-3.

6.1.1.1 Thermal behavior

After conducting the simulation, the results were presented for a 48-hour timeframe, highlighting the most extreme temperatures: the lowest temperatures in January and the highest temperatures in July. This section focuses on presenting the findings of our study, which aimed to track the fluctuations in the indoor temperature of Room 1. As the temperature is one of the critical factors that affect the indoor environment's thermal comfort, we aimed to investigate the changes in Room 1's temperature over time. By monitoring these variations, we can gain insights into the effectiveness of insulators with different thicknesses in maintaining a comfortable indoor environment. Therefore, in this section, we provide a detailed analysis of the indoor temperature fluctuations in Room 1 and the impact of various insulators on thermal comfort.

Figures 6-3 and 6-4 illustrate the fluctuations in the internal temperature of room 1 with types of insulation of various thicknesses. Specifically highlight the maximum and minimum temperatures observed during the year, which correspond to the months of January and July.

Figure 6-3 presents an analysis of the internal temperature variations in January for different types of insulation materials of varying thicknesses. The figure is divided into four subfigures, where each subfigure shows the temperature readings for a particular insulation thickness.

Upon examining Figure 6-3a, it is clear that when the insulation thickness is 3 cm, the wood fiber insulation material exhibits the highest temperature of 0.05°C compared to the other insulation materials. Thus, in this case, wood fiber can be regarded as the best insulator among the other materials. Moving on to Figure 6-3b, which represents the temperature readings for a thickness of 6 cm, both wood fiber and glass wool insulation materials recorded the highest temperature, with a difference of 0.04°C compared to expanded polystyrene and rock wool insulation materials. As a result, both wood fiber and glass wool are deemed to offer the best insulation in this particular case.

Figure 6-3c shows the temperature readings for an insulation thickness of 9 cm. In this case, wood fiber insulation material recorded a temperature that is 0.02°C higher than glass wool insulation material, and 0.04°C and 0.06°C higher than expanded polystyrene and rock wool insulation materials, respectively. Thus, in comparison, wood fiber insulation material offers the best temperature among the other insulation materials for this particular insulation thickness.

Finally, Figure 6-3d represents the temperature readings for an insulation thickness of 12 cm. In this case, wood fiber insulation material recorded the best results with a temperature that is 0.02 °C, 0.03°C and 0.06°C higher than glass wool, polystyrene and rock wool insulation materials, respectively. Therefore, from Figure 5, we can conclude that in the case of an insulation thickness of 3 cm, 6, 9, and 12 cm, wood fiber is the best insulator and exhibits the highest temperature compared to other insulation materials.

Figure 6-4 illustrates the fluctuations in internal temperature during the hottest month of the year, which is July. As we can see from Figure 6-4a, wood fiber has recorded the lowest temperature compared to other insulators, which indicates that it performs better in preventing heat from entering the room. This could be because of the unique structure of wood fiber insulation, which offers high thermal resistance, making it an excellent insulator for hot temperatures.

Moreover, Figures 6-4b and 6-4c show that when the thickness of the insulation is 6 cm and 9 cm, wood fiber provided the best insulation performance, resulting in a lower temperature of 0.01°C compared to each insulator, glass wool, and rock wool, and 0.02°C compared to expanded polystyrene. This is a significant result as it indicates that wood fiber is an excellent insulator for different thicknesses and can maintain the internal temperature at the lowest point compared to other insulators. The lower the internal temperature, the less the need for air conditioning and cooling systems, which reduces energy consumption and costs.

Furthermore, Figure 6-4d highlights that when the insulation thickness is 12 cm, wood fiber performs the best as an insulator, offering a lower temperature of 0.01°C compared to glass wool and 0.02°C compared to expanded polystyrene and rock wool. This indicates that wood fiber is the most effective insulation material in preventing heat transfer, which can be beneficial in reducing energy consumption and costs associated with cooling systems in the summer months.

In conclusion, these results demonstrate that wood fiber is the most efficient insulation material for reducing heat transfer and maintaining a lower temperature inside the room during the hottest months of the year. By choosing the right insulation material and thickness, we can reduce energy consumption and costs associated with cooling systems, and contribute to a more sustainable and energy-efficient future.

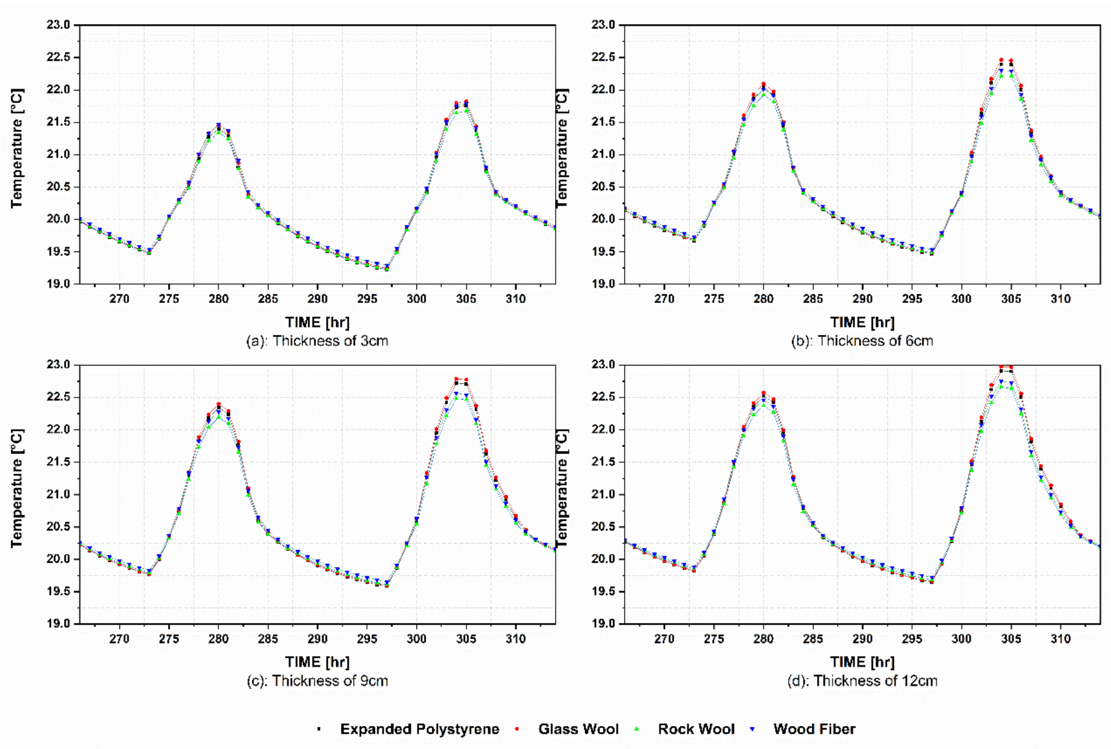


Figure 6-3 January temperatures with varying thicknesses of insulating materials where: (a) 3 cm; (b) 6 cm; (c) 9 cm; (d) 12 cm

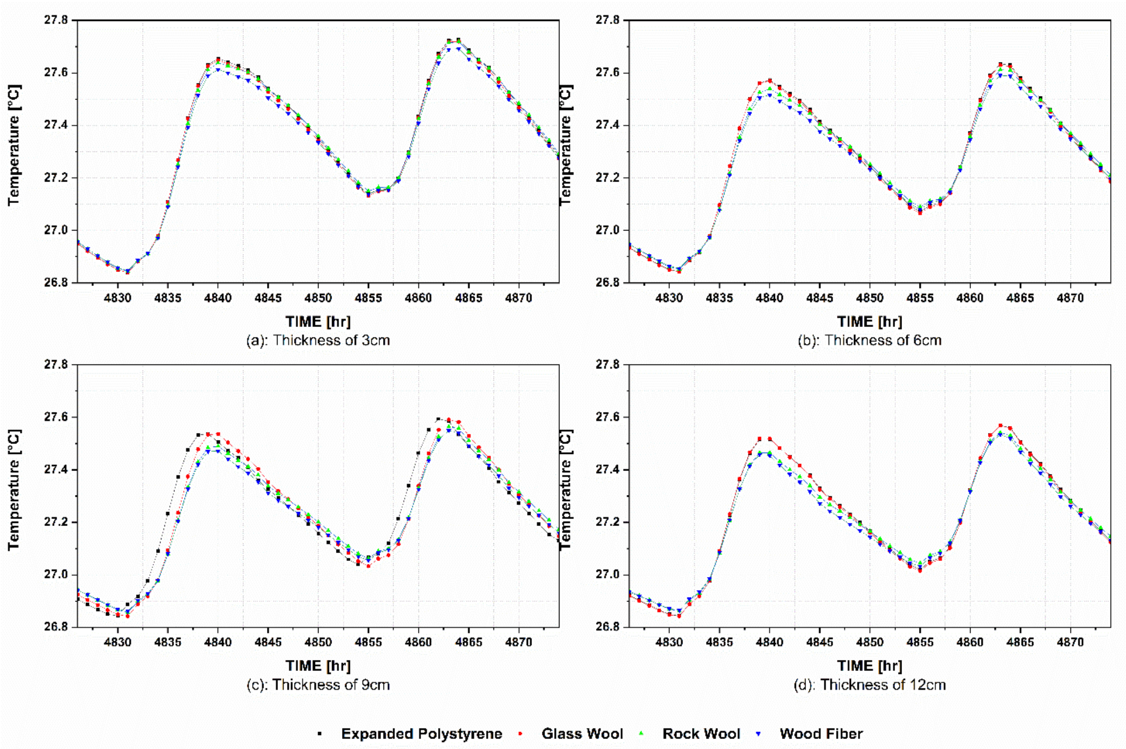


Figure 6-4 July temperatures with varying thicknesses of insulating materials where: (a) 3 cm; (b) 6 cm; (c) 9 cm; (d) 12 cm

Based on the analysis presented in Figures 6-3 and 6-4, it can be concluded that the selection of insulation materials and their thicknesses can have a significant impact on the internal temperature of indoor environments, particularly in extreme weather conditions such as in the winter and summer months. Wood fiber insulation material is found to be the best among the other insulation materials, and it performs better when the outside temperature is low, and it offers the best insulation performance for different thicknesses, resulting in a lower temperature compared to other insulators. On the other hand. By selecting the right insulation material and thickness, we can reduce energy consumption and costs associated with heating and cooling systems, which contributes to a more sustainable and energy-efficient future.

6.1.1.2 Energy behavior

In this particular section, the main emphasis is on the computation of the yearly heating and cooling requirements for each insulation material and thickness, as shown in Figures 6-5 and 6-6. The primary objective is to determine which of these insulators has the potential to offer the most effective energy-saving. The results of this analysis have been compiled in the form of annual heating and cooling load data for each insulation material and thickness.

These figures provide a clear visual representation of the energy consumption required to maintain a desired temperature within a given space throughout the year. By comparing the data for different insulation materials and thicknesses, it becomes possible to identify which materials offer the most efficient thermal insulation and which thicknesses provide the optimal balance between insulation performance and cost-effectiveness.

Ultimately, the aim of this analysis is to provide valuable insights into the most effective ways of reducing energy consumption and lowering heating and cooling costs also reduces the environmental impact of energy consumption. By choosing the appropriate insulation material and thickness.

Figure 6-5 depicts the annual heating demands associated with different insulators and thicknesses. The results show that there are significant differences in energy usage depending on the type of insulator and thickness chosen.

When the insulation thickness is either 3 cm or 6 cm, we observe that significant energy savings of 4% compared to glass wool and 6% compared to both expanded polystyrene and rock wool can be achieved. This indicates that at these thicknesses, certain insulators are more effective in reducing heating demands and offer better energy savings compared to others.

Additionally, when the insulation thickness is increased to 9 cm and 12 cm, the results show that using wood fiber insulation can lead to considerable energy savings. Specifically, when compared to glass wool, rock wool, and expanded polystyrene, using wood fiber insulation can result in savings of 4%, 5%, and 6% respectively. This suggests that at higher insulation thicknesses, wood fiber insulation is a more efficient option for reducing heating demands and improving energy efficiency.

It is worth noting that the thickness of the insulation material is also a critical factor in determining its effectiveness. The thicker the insulation material, the better its performance at reducing heating demands. This is illustrated in Figure 6-5, where thicker insulation materials consistently require less heating compared to thinner ones.

In fact, when comparing the performance of wood fiber insulation to other insulation materials across all thicknesses tested, wood fiber consistently outperforms other materials by saving more than 4% in heating load reduction. This reinforces the idea that wood fiber insulation is a reliable and effective choice for energy-efficient building design.

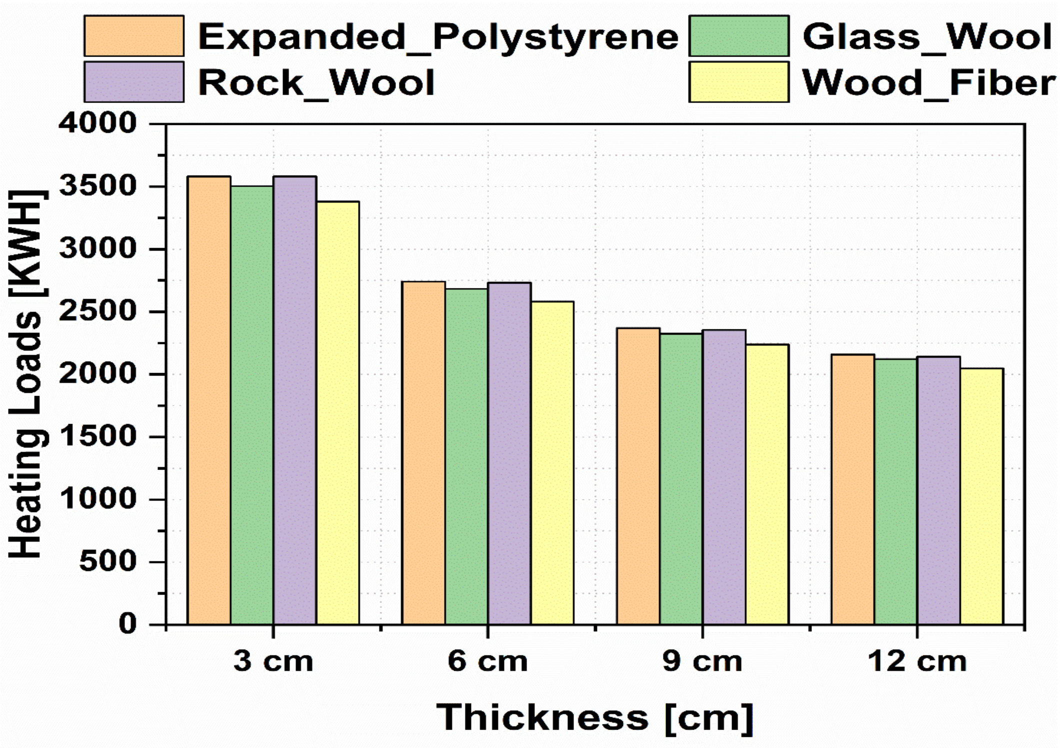


Figure 6-5 Heating loads for the insulators with various thicknesses

Turning to Figure 6-6, we can see that wood fiber insulation also offers some savings in terms of cooling load reduction, with reductions of 1% to 2% across all thicknesses and compared to other insulation materials. While these savings may not be as significant as those associated with heating load reduction, they are still notable and can contribute to overall energy efficiency and cost savings in a building.

These results highlight the effectiveness of wood fiber insulation as a choice for reducing both heating and cooling loads. By selecting an insulation material and thickness that offer the best performance in terms of reducing both heating and cooling demands, significant energy savings can be achieved, resulting in cost savings and environmental benefits.

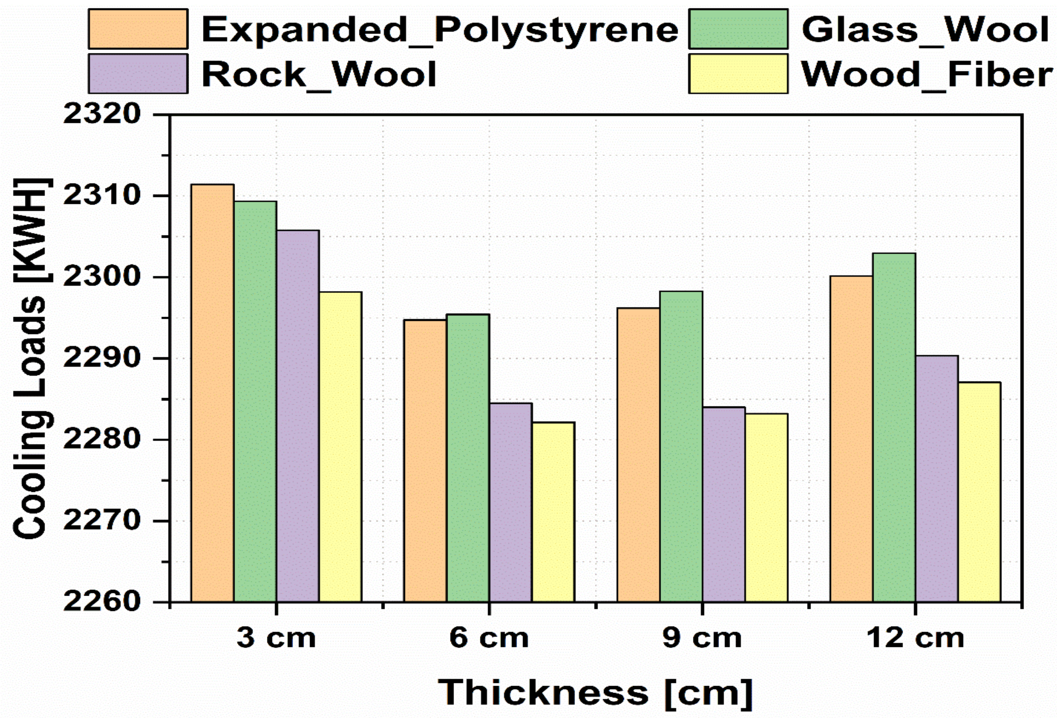


Figure 6-6 Cooling loads for the insulators with various thicknesses

We can conclude that the selection of insulation material and thickness plays a critical role in reducing energy consumption and achieving cost savings in a building. The study indicates that wood fiber insulation consistently outperforms other insulation materials across different thicknesses tested in terms of reducing heating load. Furthermore, wood fiber insulation also offers some savings in terms of cooling load reduction, contributing to overall energy efficiency and cost savings. The study suggests that selecting an insulation material and thickness that offer the best performance in reducing both heating and cooling demands can lead to significant energy savings, resulting in cost savings and environmental benefits. However, it is essential to consider various factors such as climate, building design, construction materials, and intended use when selecting insulation materials and thicknesses. We can conclude that the selection of insulation material and thickness plays a critical role in reducing energy consumption and achieving cost savings in a building. The study indicates that wood fiber insulation consistently outperforms other insulation materials across different thicknesses tested in terms of reducing heating load. Furthermore, wood fiber insulation also offers some savings in terms of cooling load reduction, contributing to overall energy efficiency and cost savings. The study suggests that selecting an insulation material and thickness that offer the best performance in reducing both heating and cooling demands can lead to significant energy savings, resulting in cost savings and environmental benefits. However, it is essential to consider various factors such as climate, building design, construction materials, and intended use when selecting insulation materials and thicknesses.

In this context, it was observed that increasing insulation thickness beyond a certain limit does not lead to significant improvements in energy savings. Thus, to optimize the balance between insulation performance and cost-effectiveness, insulation with a thickness of 9 cm was selected.

The analysis also compared the effectiveness of different insulation materials in terms of reducing heating and cooling loads. Based on the results obtained, wood fiber insulation was found to be the best insulator. This conclusion was drawn by monitoring the internal temperature of room 1 and analyzing the annual heating and cooling loads for each insulation material and thickness.

Figures 6-7 and 6-8 demonstrate the changes in indoor thermal fluctuations and the resulting energy savings achieved through the modification of wood fiber insulation thickness. The study revealed that adjusting the thickness of wood fiber insulation from 3 cm to 9 cm resulted in a savings of over 23% of the heating and cooling loads.

The results obtained from this analysis provide strong justifications for using wood fiber insulation with a thickness of 9 cm. This choice can help to achieve significant energy savings, reduce heating and cooling costs, and minimize the environmental impact of energy consumption.

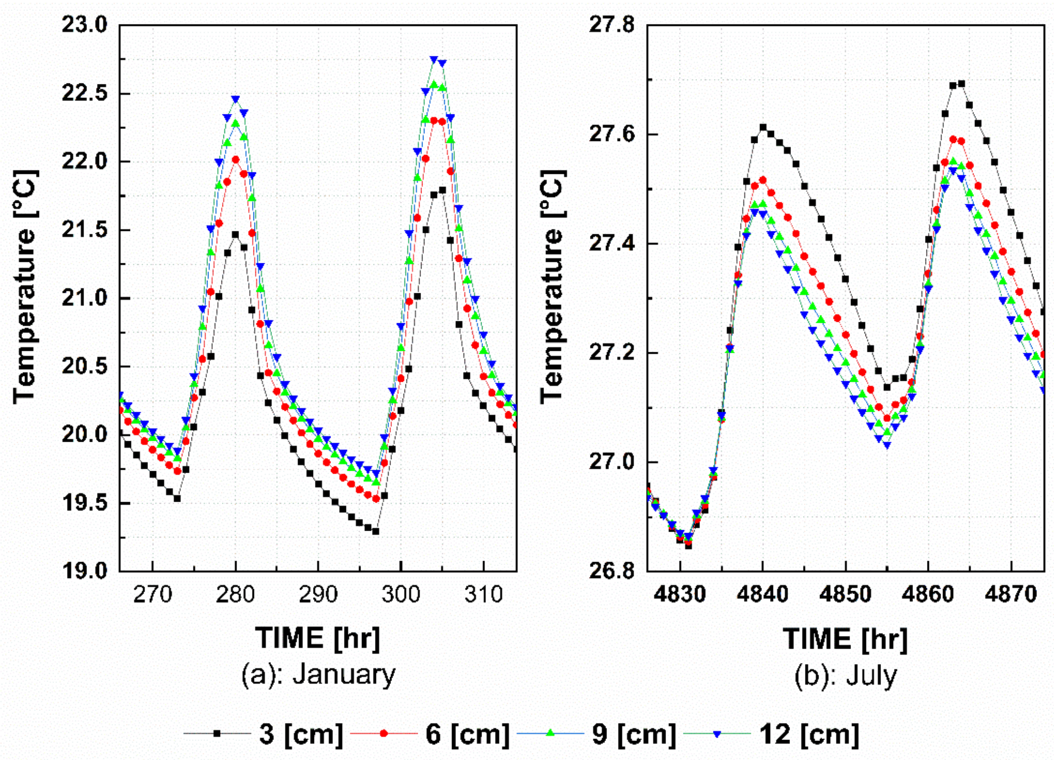


Figure 6-7 Distribution of the insulator wood fiber temperature where: (a) January; (b) July

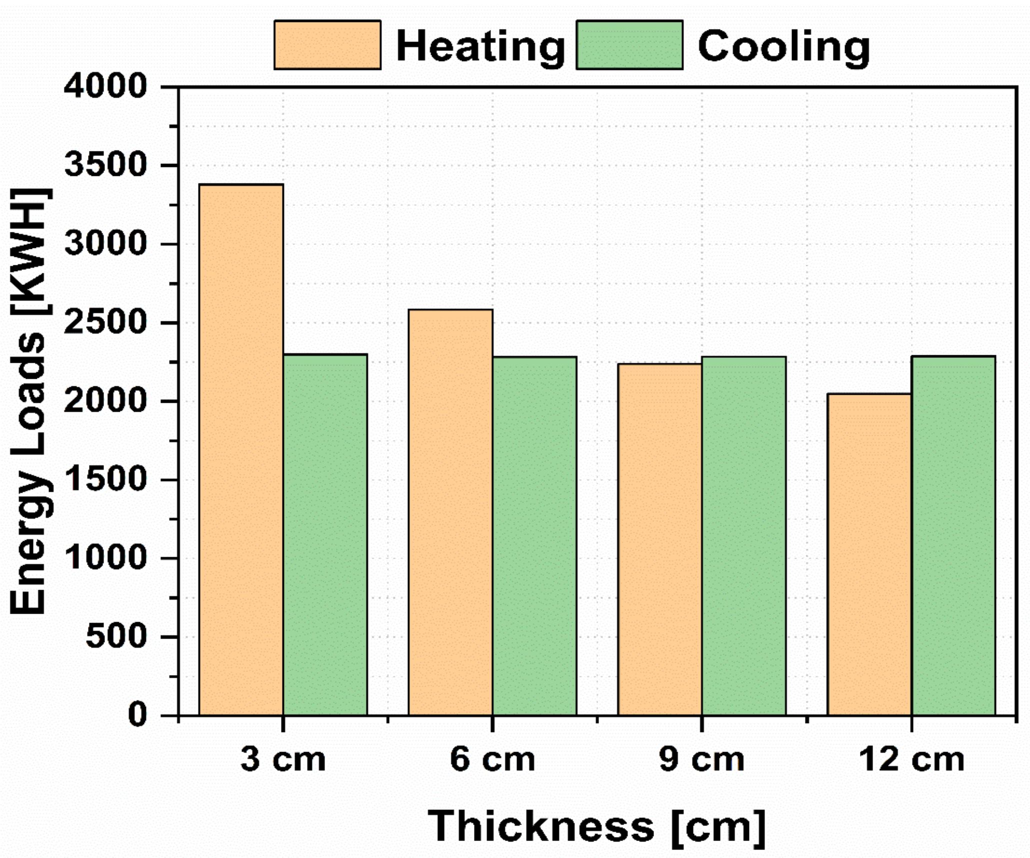


Figure 6-8 Heating and cooling requirements for the insulator wood fiber

Based on the results obtained from the analysis of the annual heating and cooling requirements for different insulation materials and thicknesses, using wood fiber insulation with a thickness of 9 cm can provide the most effective energy-saving. The results of this analysis, as depicted in Figures 6-4, 6-5, 6-7, and 6-8, indicate that the insulation thickness is a critical factor in determining the efficiency of the insulation material, and thicker insulation materials generally perform better at reducing heating and cooling demands.

Moreover, the results show that wood fiber insulation outperforms other insulation materials across all thicknesses tested, by offering energy savings of more than 4% in heating load reduction compared to other insulators. Specifically, when the insulation thickness is 9 cm, using wood fiber insulation can result in energy savings of 4% compared to glass wool, 5% compared to rock wool, and 6% compared to expanded polystyrene.

Based on these findings, it can be concluded that using wood fiber insulation with a thickness of 9 cm can provide effective thermal performance and energy efficiency, resulting in significant energy savings and cost reductions for heating and cooling loads. Therefore, if the objective is to reduce energy consumption and lower heating and cooling costs while reducing the environmental impact of energy consumption, then using wood fiber insulation with a thickness of 9 cm can be a suitable choice.

6.1.1.3 Comparison of present results with previous studies:

In this section, represent a comparison with previous study. Eddib and Lamrani [311]; have been compared with our investigation. In terms of similarities, the studies aim to investigate the impact of different insulation materials and thicknesses on the energy efficiency and thermal comfort of buildings under different climatic conditions. They use numerical simulations through using TRNSYS to evaluate the performance of different insulation materials and thicknesses and provide recommendations for the most suitable materials and thicknesses for specific climates. Additionally, all studies emphasize the importance of proper insulation for reducing energy consumption, improving indoor comfort, and achieving sustainable building designs.

In terms of differences, the studies differ in their geographic scope, insulation materials and thicknesses evaluated, and specific findings. Eddib and Lamrani [311], studied the impact of different insulation materials, including expanded Polystyrene, glass wool, rock wool, and wood fiber of different thicknesses (2 cm, 4 cm, 6 cm, and 8 cm) on the thermal and energetic performance of the envelope of a house located in Marrakesh City, Morocco. Similarly, the study on evaluating the impact of insulation and glazing on the energy efficiency of houses in the Mediterranean climate focuses on determining the optimal thermal insulation and the best glazing for the building envelope in the Mediterranean region where the province of Ain Temouchent, Algeria, was taken in this study.

In terms of results, Eddib and Lamrani [311] found that an 8 cm thickness of wood fiber insulation was the most effective, resulting in a 7% reduction for heating and 14% for cooling loads. The current study found that wood fiber insulation with a 9 cm thickness provided the best thermal performance, resulting in a 26% reduction in energy costs compared to 3cm of expanded polystyrene. Regarding temperature changes, Eddib and Lamrani [311] found that in January, temperatures were higher by 0.26°C, and in July, temperatures were lower by 0.49°C. The current study found that in January, temperatures were higher by 0.47°C, and in July, temperatures dropped by 0.13°C. Overall, both studies provide valuable insights into the effectiveness of different insulation types and optimal thicknesses in their respective regions.

As a conclusion for this section, it can be mentioned that all studies provide valuable insights into the importance of proper insulation and glazing for reducing energy consumption, improving indoor comfort, and achieving sustainable building designs under different climatic conditions. They demonstrate the significance of choosing the right insulation materials and thicknesses for specific climates and building designs and emphasize the need for further research and experimentation to validate the numerical results found.

Table 6-1 Comparison with previous studies

Researchers	Location	Climate zones (Köppen climate classification)	Optimum Insulators	Optimum insulation thickness (cm)	Results
Present study	Ain Temouchent, Algeria	Mediterranean climate	Wood fibre	9	Energy saving 26%
Eddib and Lamrani [311]	Marrakesh, Morocco	Semi-arid climate	Wood fibre	8	Energy saving 21%

6.1.2 The influence of glazing on the interior environment and energy loads

This section deals with the investigation of how glazing affects the indoor environment of room 1 and the heating and cooling loads of the entire building. Glazing refers to the transparent part of a building's façade that allows natural light into the interior spaces.

The amount and type of glazing used in a building can have a significant impact on the building's energy consumption and indoor environment.

The investigation involved monitoring the indoor environment of room 1 and the heating and cooling loads of the entire building under different glazing conditions. By measuring the temperature and humidity levels in room 1 and the energy consumption of the building's heating and cooling systems, the impact of glazing on the building's energy performance and the indoor environment was assessed.

The findings of this investigation are critical for building designers and owners as they determine the optimal glazing conditions that balance energy efficiency and occupant comfort. By understanding how glazing affects the building's energy consumption and indoor environment, it is possible to make informed decisions about the design and construction of a building's façade.

6.1.2.1 Thermal behavior

This part of the study aimed to investigate the influence of glazing on the indoor environment of the building. Glazing is a critical element in the building envelope that can affect the thermal comfort of occupants. Therefore, this study explored the impact of various types of glazing on the indoor environment.

The types of glazing studied in this research included triple, double, and simple glazing, with different levels of emissivity and Argon filling. Figure 6-9 summarizes the results of the study, showing the indoor temperature during the winter and summer seasons for January and July, respectively.

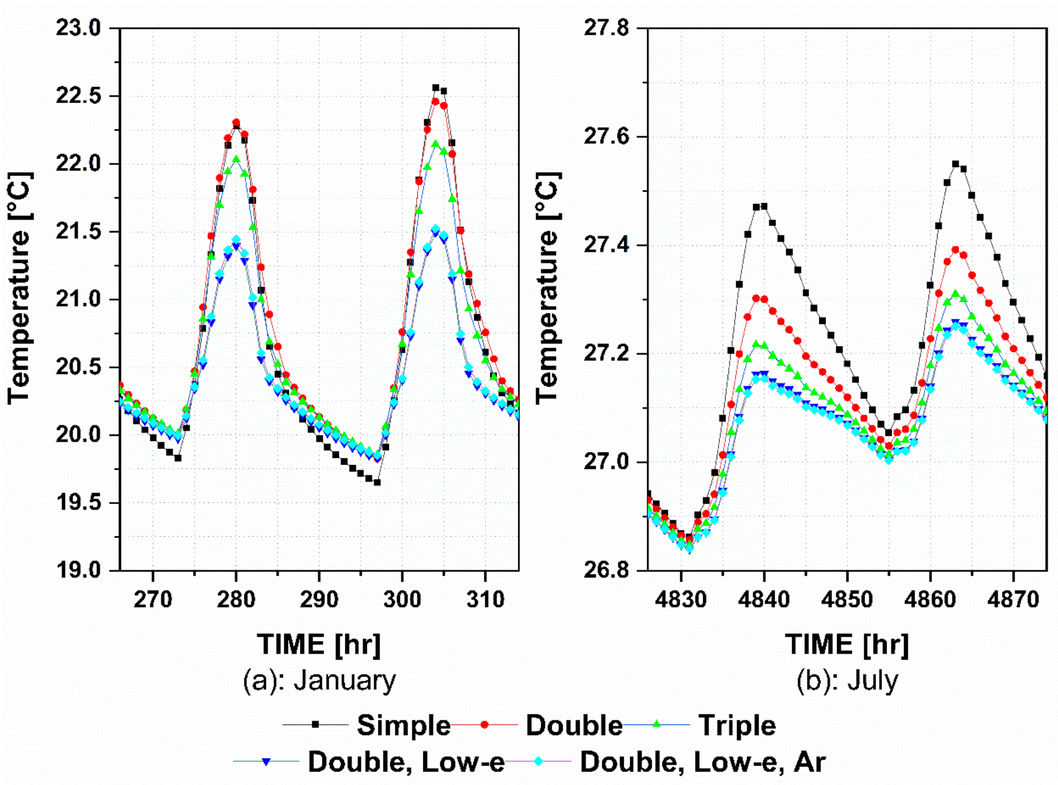


Figure 6-9 Window glazing impact on the interior environment: (a) January; (b) July

Figure 6-9a indicates that double-glazing provided the best internal temperature, with a difference of 0.11°C when compared to simple glazing and triple glazing. Moreover, the double-glazing low emissivity and double-glazing low emissivity filled Argon showed the lowest temperature compared to the other forms of glazing. The comparative ratios were 0.03, 0.07, and 0.15°C for each of the triple, double, and simple glazing, respectively. This suggests that double-glazing is the most efficient option for maintaining a comfortable indoor temperature in the coldest months.

Figure 6-9b demonstrates that the double-glazing low emissivity and double-glazing low emissivity filled Argon types of glazing provided the lowest temperature compared to the other types of glazing. The comparison ratios were 0.03, 0.07, and 0.15°C for each of the triple, double, and simple glazing, respectively. This shows that double-glazing low-emissivity filled Argon is the most efficient option for maintaining a comfortable indoor temperature in the hottest months. Therefore, these types of glazing are highly efficient and suitable options for maintaining a comfortable indoor temperature throughout the year.

6.1.2.2 Energy behavior

This section of the study aimed to investigate the energy-saving potential of different types of glazing. The results showed that double glazing was the most energy-efficient option, providing the lowest heating loads when compared to other types of glazing. In fact, double glazing can save up to 23% of heating loads when compared to single glazing, as shown in Figure 6-10. In terms of cooling loads, adopting double glazing instead of single glazing can save more than 10%.

One of the significant advantages of double glazing is that it is a practical option that comes with comparable costs to single glazing.

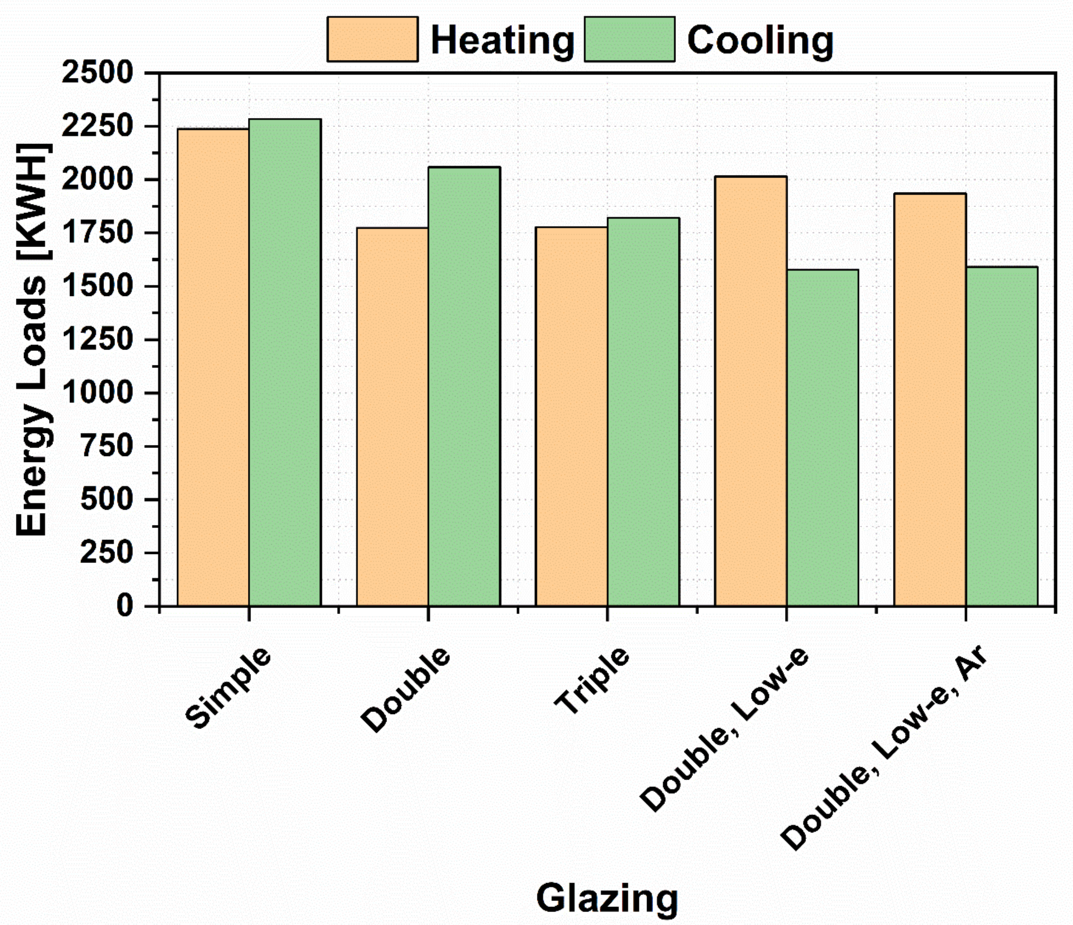


Figure 6-10 Heating and cooling demands of different glazing types

These findings highlight the importance of choosing the right type of glazing for buildings to achieve energy efficiency and cost-effectiveness. Double glazing is a practical and cost-effective option that can provide significant energy savings, making it an excellent choice for the majority of building orientations. However, for the southern side of buildings, double glazing with low emissivity is the most suitable option for achieving optimal energy efficiency.

It can be concluded that glazing has a significant impact on both the thermal indoor environment and the energy consumption of a building. The study found that double glazing is the most efficient option for maintaining a comfortable indoor temperature in both the hottest and coldest months, with double glazing low emissivity filled Argon being the most energy-efficient option.

In terms of energy consumption, double glazing was found to be the most energy-efficient option, providing significant savings in heating and cooling loads when compared to single glazing. The study also showed that double glazing is a practical and cost-effective option, making it an excellent choice for the majority of building orientations, particularly for the eastern, northern, and western sides.

Overall, the findings of the study highlight the importance of considering the type of glazing used in buildings and how it can impact energy consumption and efficiency. Selecting the appropriate glazing for the building's orientation and location can result in substantial energy savings and cost reduction.

6.1.2.3 Comparison of present results with previous studies

Almarzouq and Sakhrieh [261] conducted a study on a residential building in Amman, Jordan to investigate the effects of replacing single glazing with double glazing filled with Argon gas and low emissivity coating on energy consumption and thermal comfort. In contrast, our study focused on a house located in the Mediterranean region, specifically in the province of Ain Temouchent, Algeria, to evaluate the effectiveness of various glazing types for reducing heating and cooling costs.

Both studies share a similarity in finding double glazing to be more energy-efficient than single glazing. Almarzouq and Sakhrieh [261] discovered that replacing single glazing with double glazing with low emissivity coating can save 24.7% of consumed energy, while our study found that upgrading from single to double glazing can reduce heating and cooling costs by 23% and 10%, respectively. Additionally, both studies recommend using double glazing as a practical and cost-effective option for most building orientations. However, our study adds the suggestion that double glazing with low emissivity is the best choice for the southern side of the building to achieve optimal energy efficiency, resulting in energy savings of more than 4% for heating and cooling loads compared to double and single glazing.

Both studies emphasize the importance of choosing appropriate glazing materials and insulation in building design to achieve optimal indoor comfort and energy efficiency.

6.2 Primary School

This section delves into the outcomes of our investigation into the thermal and energetic behaviors of primary school classrooms in the Mediterranean climate of Ain Temouchent Wilaya, specifically in the Khoualed Abdel Hakem village, Algeria. Focused on optimizing energy performance, we explore the impact of key passive strategies, including external shading devices, WWR, glazing types, and building envelope adjustments. Building upon the meticulous exploration highlighted in the conclusion, our results, grounded in rigorous analysis and supported by TRNSYS 17 simulations, offer valuable insights into the effectiveness of these passive strategies. From optimal WWR to the role of external shading devices, and glazing types, this section presents a comprehensive understanding of how these strategies contribute to the overall energy performance of educational facilities in a Mediterranean climate.

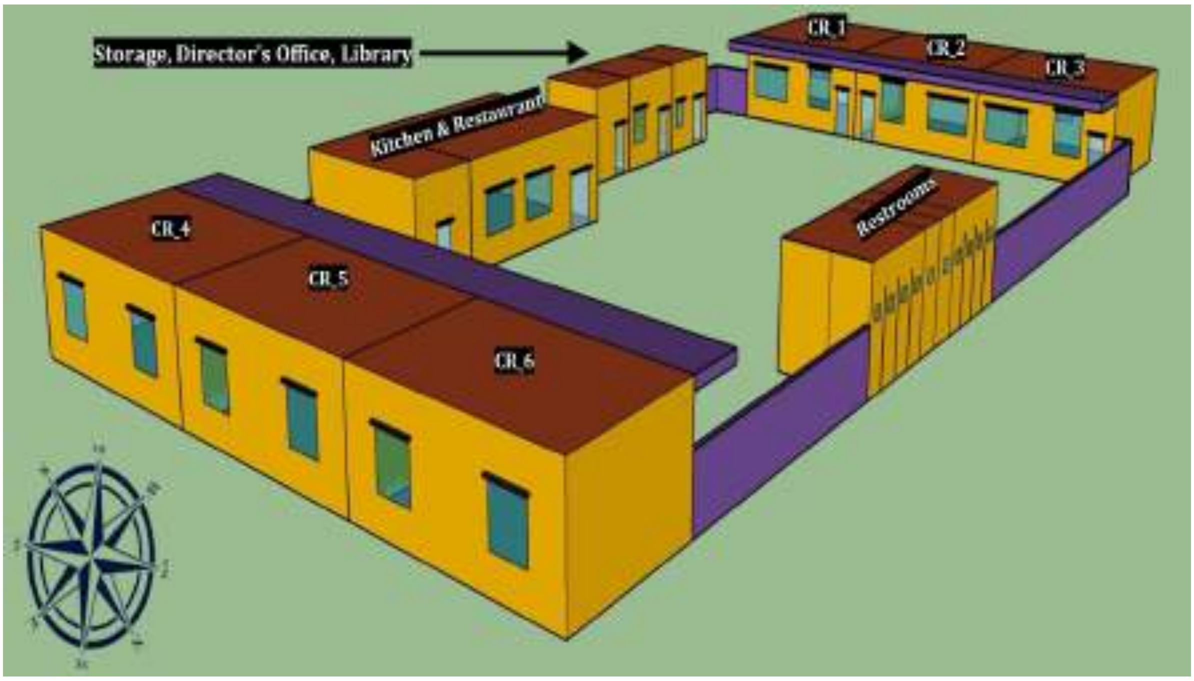


Figure 6-11 A 3D schematic for the studied primary school

Electricity and gas are the main sources of energy for Algerian buildings, used for heating and cooling. In our case, the energy systems used for heating and cooling are air conditioners. The school's energy consumption was 6,775 kWh per year, according to the electricity and gas bills of the primary school.

Figure 6-11 depicts a detailed 3D schematic representation of the primary school being examined. This schematic is a useful tool that offers a comprehensive visualization of the educational facility being evaluated.

6.2.1 Validations

Following an extensive and in-depth bibliographic review of research on thermal performance, energy efficiency in buildings, and passive strategies for achieving environmentally friendly designs, this section will validate the credibility of our simulations for the primary school by comparing the obtained results with actual energy consumption bills on a quarterly and annual basis.

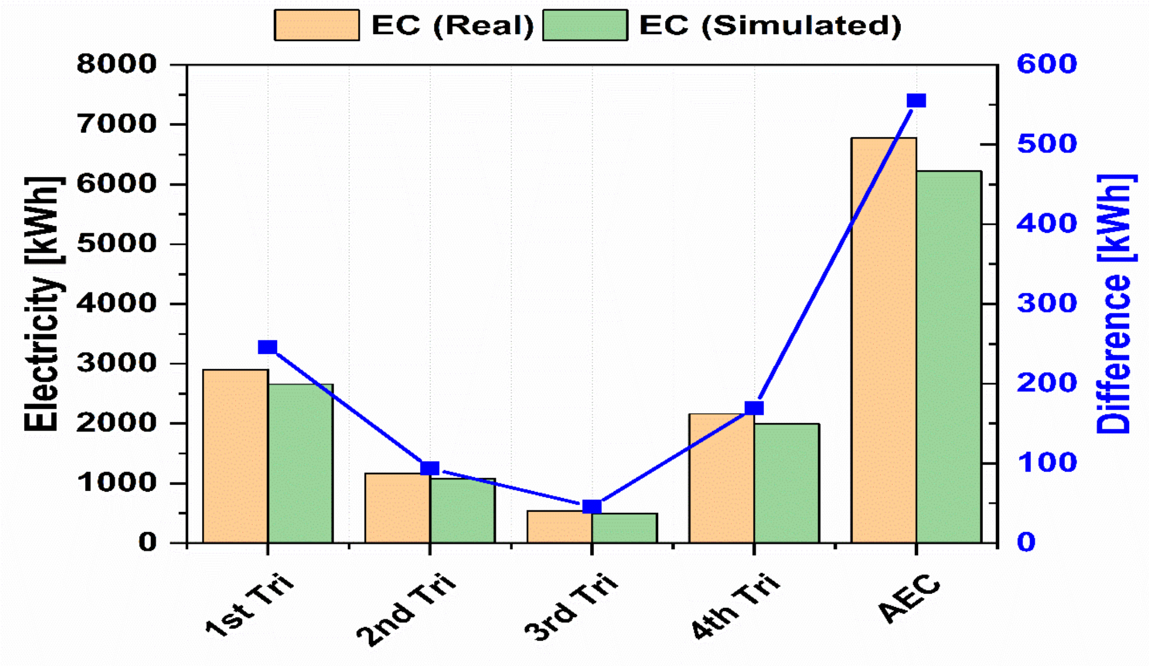


Figure 6-12 Comparison between the real and simulated energy consumption of the primary school

In the validation section, we present a detailed comparison between actual and simulated electricity consumption bills, as illustrated in Figure 6-12. To provide a comprehensive understanding of the validation process, it is crucial to elucidate the input parameters employed in our simulation model. These parameters encompass occupancy patterns, climate data, building envelope characteristics (such as insulation and glazing), internal heat gains (from lighting, equipment, and occupants), and HVAC system performance—factors that collectively influence energy consumption. Analyzing the quarterly data, we observed a close match between simulated and actual values, with differences ranging from 45.77 kWh to 246.07 kWh across the four quarters. Similarly, the annual energy consumption simulation, totaling 6219.81 kWh, closely aligns with the actual value of 6775 kWh, exhibiting a mere 8% difference. Despite an underestimation of actual energy consumption, the simulation accurately captures overall trends and patterns. This robust congruence suggests that our simulation model, bolstered by carefully selected input parameters, is reasonably accurate and serves as a valuable tool for predicting and analyzing electricity consumption.

In Figure 6-13, the annual heating and cooling requirements of each facility within the primary school are presented, derived from the simulated results. The electricity consumption for heating and cooling is shown for each facility. The heating needs range from 56.03 kWh to 227.10 kWh, while the cooling needs range from 90.07 kWh to 696.11 kWh. Notably, the classroom (CR_1) in the southwest has the highest cooling demand with a cooling consumption of 696.11 kWh. Alternatively, classroom 6 (CR_6), located in the northeast, has the highest heating demand with a heating consumption of 227.10 kWh.

Based on our analysis, the focus of our study will be on CR_1 and CR_6, which represent the extreme cooling and heating requirements, respectively. The significant cooling requirement of CR_1 and its location in the southwest make it an interesting facility to investigate. Meanwhile, CR_6's substantial heating demand in the northeastern part of the school presents another crucial area for further examination. By understanding and optimizing the energy consumption of these facilities, we can make informed decisions to improve the energy efficiency and comfort of the primary school.

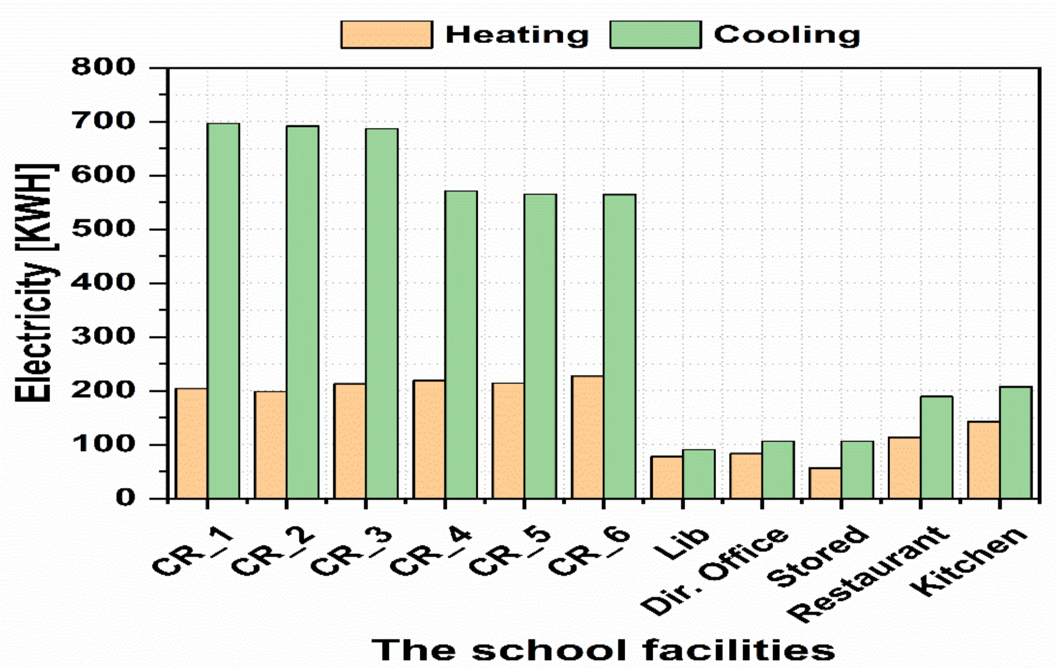


Figure 6-13 Annual heating and cooling demands for the primary school facilities

6.2.2 Shading devices

Shading devices, known as sunshades or sunscreens, are crucial architectural elements designed to regulate sunlight entry and mitigate its effects inside buildings, optimizing energy conservation and indoor comfort.

External shading structures control sunlight influx, reducing solar heat absorption in summer and providing insulation in winter, thus stabilizing indoor temperatures.

The VSA and Horizontal Shading Angle (HSA) are crucial for improving comfort, energy efficiency, and building performance (see Figure 3-3). Depending on factors like orientation and climate, either vertical or horizontal shading may be preferred, or a combination of both. Our study, focusing on the VSA, reveals that it significantly impacts thermal and energy behavior in classrooms, unlike the HSA, which has minimal impact according to Figure 6-14.

In conclusion, our research underscores the significant influence of shading devices on classroom temperatures, particularly in extreme summer conditions. Adjusting the VSA can lead to noticeable temperature changes, informing shading strategy decisions and optimizing thermal comfort.

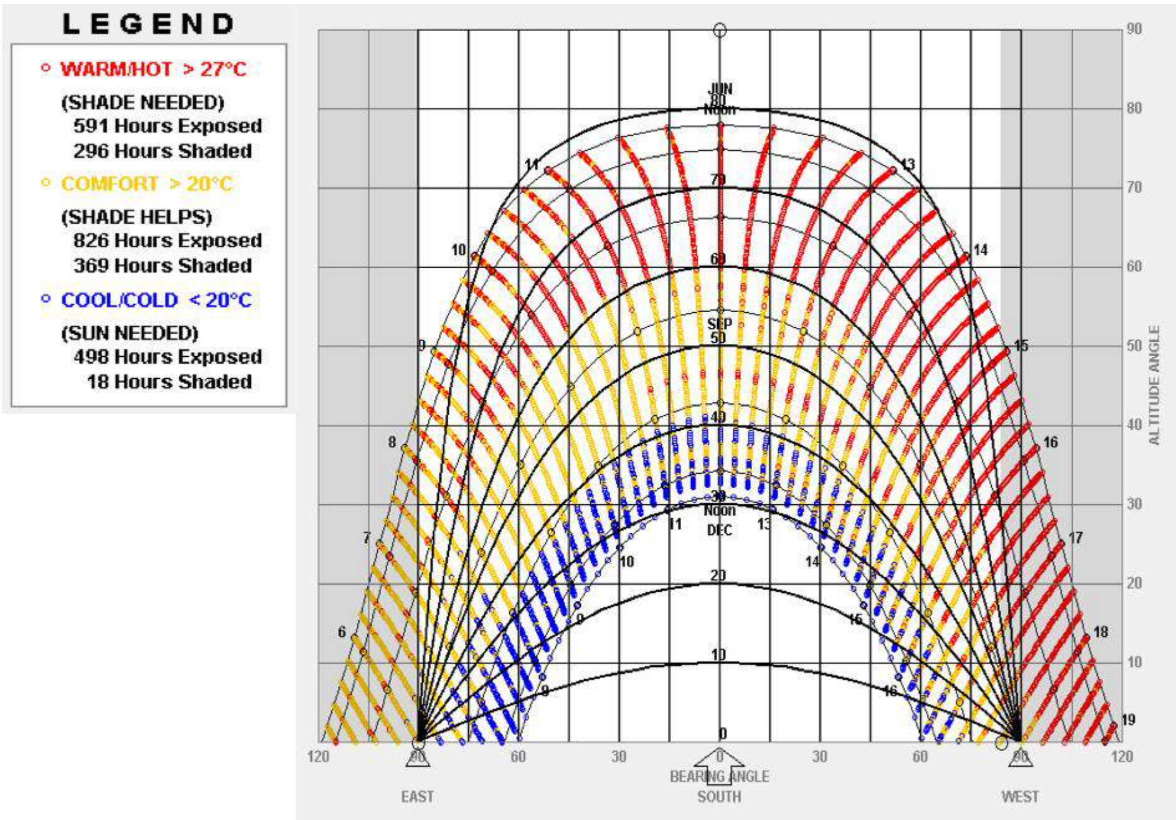


Figure 6-14 Sun shading chart of the studied region in summer and fall: Effect of Horizontal Shading Angle (HSA)

6.2.2.1 Thermal behavior:

This section provides a comprehensive examination of the influence of shading devices impact the internal temperature of classrooms, focusing on scenarios devoid of heating and cooling mechanisms. By analyzing temperature fluctuations in Classroom 1 (Tin_CR1) and Classroom 6 (Tin_CR6) during extreme weather, considering their differing orientations (Classroom 1 facing southwest and Classroom 6 northeast), the study offers valuable insights. Figures 6-15 and 6-16 present a detailed comparison, emphasizing the effect of the VSA and the room's current state. Notably, Classroom 1 consistently registers higher temperatures than Classroom 6 due to its southwest positioning and prolonged exposure to direct sunlight, resulting in increased solar heat gain.

Figures 6-15a and 6-16a illustrate temperature changes on an extreme winter day, revealing a temperature decrease with higher VSA settings, indicating a modest cooling effect.

Figures 6-15b and 6-16b showcase temperature fluctuations on an extreme summer day, indicating an average temperature reduction of 2.71°C and 2.04°C for classrooms 1 and 6, respectively, with lower VSAs resulting in cooler interiors.

The analysis underscores the efficacy of shading devices in curbing solar heat gain, thereby enhancing thermal comfort within classrooms. Notably, VSA adjustments significantly impact internal temperature, offering promising avenues for optimizing thermal comfort in both classrooms.

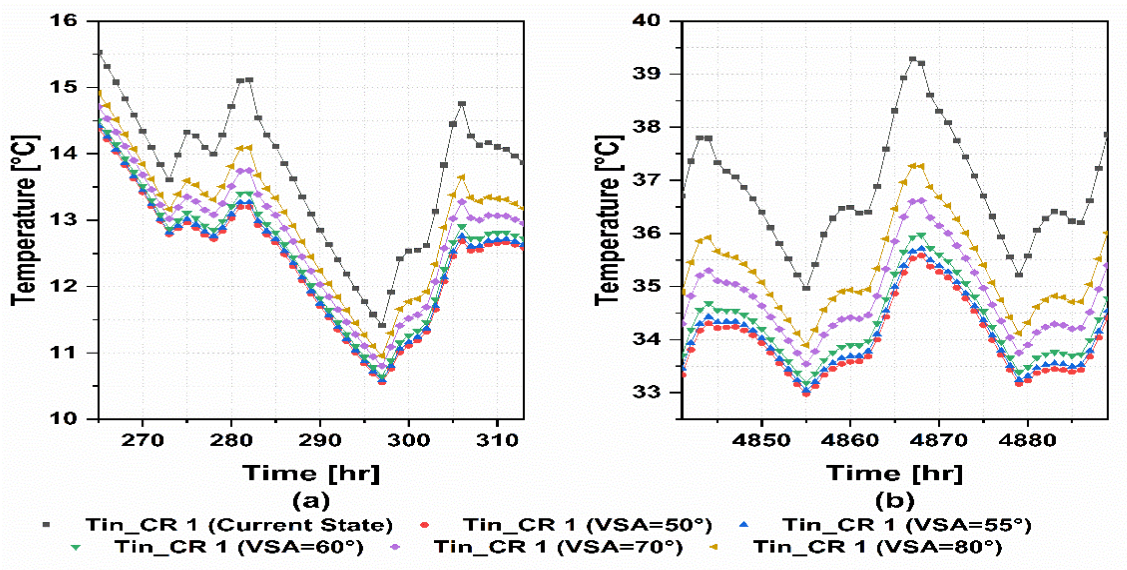


Figure 6-15 Effect of VSA on classroom 1's internal temperature: Winter (a) and Summer (b)

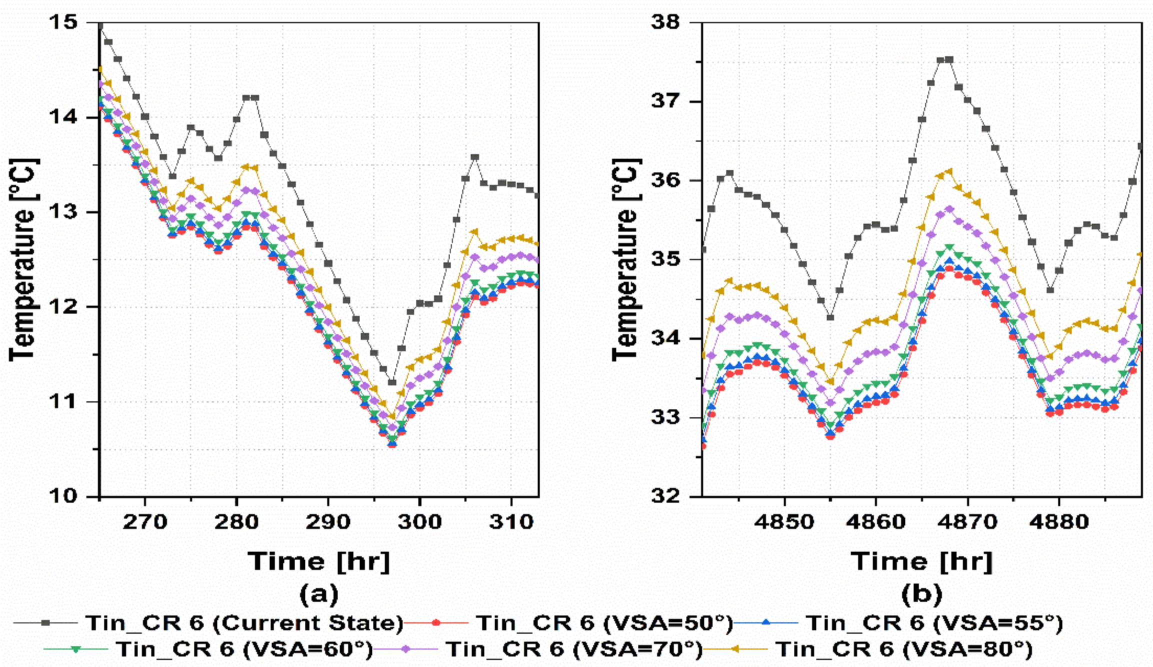


Figure 6-16 Effect of VSA on classroom 6's internal Temperature: Winter (a) and Summer (b)

Overall, the study underscores the pivotal role of VSA adjustments in modulating internal classroom temperatures, particularly during sweltering summer conditions. This understanding can inform strategic shading decisions, ultimately optimizing thermal comfort within educational spaces.

6.2.2.2 Energetics behavior:

Figure 6-17 depicts the annual energy consumption for both heating and cooling systems in classrooms 1 and 6, considering different Vertical Shading Angle (VSA) configurations. Figure 6-17a meticulously details the heating energy consumption across different VSA conditions for classrooms 1 and 6. Notably, an upward trend is observed in energy savings as the VSA increases. Classroom 1 consistently exhibits lower heating energy requirements compared to Classroom 6 across all VSA values. Remarkably, employing higher shading angles, such as VSA=80°, substantially reduces heating energy usage, indicating the efficacy of shading in curbing heat loss.

In contrast, Figure 6-17b delves into cooling energy loads, showcasing a distinctive pattern. Here, decreasing the VSA correlates with diminished cooling energy demands. Notably, VSA=50° emerges as the most efficient configuration, yielding the lowest cooling energy consumption. Conversely, elevating shading angles, particularly to VSA=80°, escalates cooling energy requirements. Classroom 1 consistently registers higher cooling energy consumption than Classroom 6 across various VSA settings.

Optimizing energy efficiency necessitates a balanced approach considering both heating and cooling systems. While higher VSA values notably reduce heating energy usage, they may inadvertently escalate cooling energy demands. Conversely, lower shading angles offer significant cooling energy savings but may lead to increased heating consumption. Adopting a VSA of 60° presents a promising solution, yielding substantial cooling energy savings of over 32% for Classroom 1 and approximately 26% for Classroom 6. This demonstrates the potential for achieving optimal energy efficiency by striking a judicious balance between heating and cooling requirements.

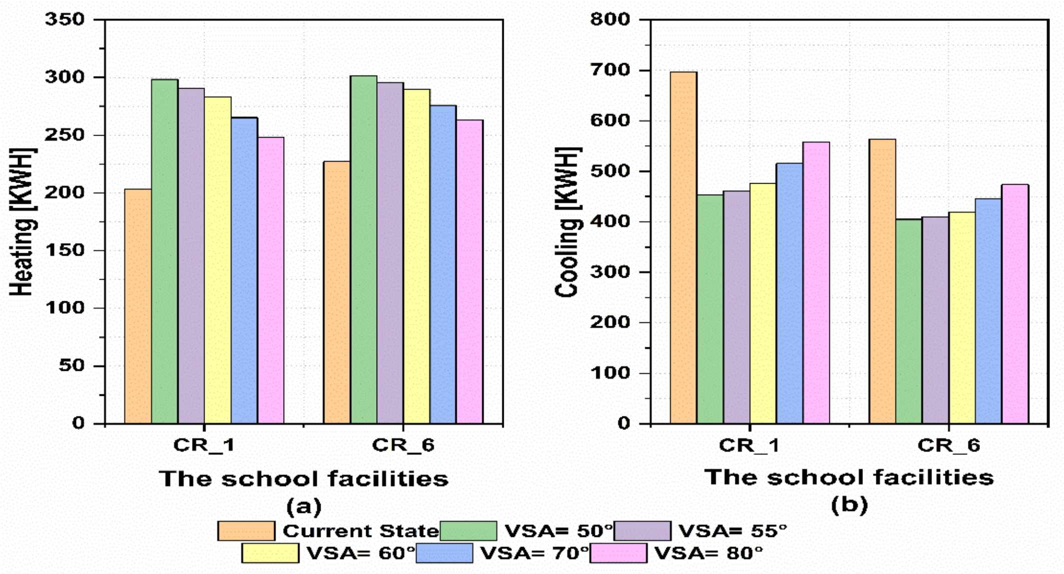


Figure 6-17 Energy loads of classrooms 1 and 6; (a): Heating, (b): Cooling

In summary, selecting VSA = 60° offers the optimal balance between heating and cooling requirements. Despite a rise in heating consumption, substantial cooling energy savings of over 32% for Classroom 1 and approximately 26% for Classroom 6 can be achieved. Moreover, overall energy load reductions of 16% for Classroom 1 and 10% for Classroom 6 signify VSA = 60° as the most energy-efficient choice, promising significant long-term energy savings.

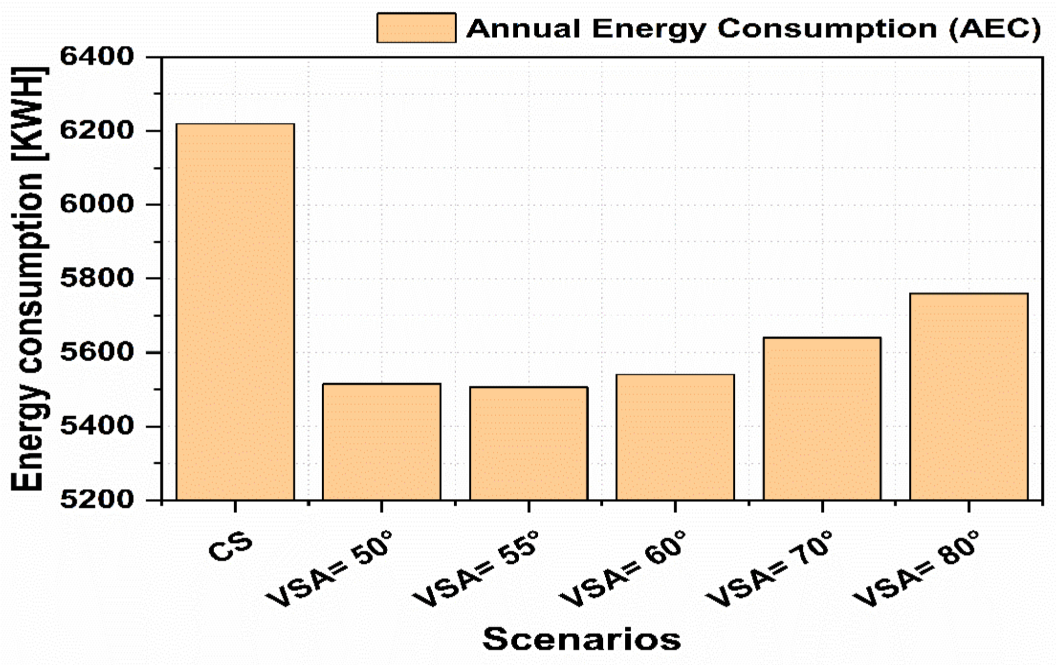


Figure 6-18 Impact of VSA on primary school annual energy demand

The effect of changing the VSA on the Annual Energy Consumption (AEC) of a primary school is depicted in Figure 6-18. It compares the AEC under different VSA scenarios to the current state.

Across all VSA scenarios, there is a consistent trend of decreasing energy consumption compared to the current state. As the VSA increases from 50° to 80°, there is a notable reduction in annual energy consumption.

In the current state, the AEC stands at 6219.81 kWh. With VSA variations, the AEC decreases significantly: 11% reduction at 50° (to 5515.19 kWh), 55° (to 5506.04 kWh), and 60° (to 5540.28 kWh). Subsequently, at 70° VSA, the AEC decreases by 9% (to 5640.52 kWh), and at 80° VSA, it decreases by 7% (to 5760.24 kWh) compared to the prevailing condition. The variance in energy consumption between the current state and each VSA scenario spans from 459.58 KWH (7%) for VSA=80° to 704.63 KWH (11%) for VSA=50°. This highlights the potential for significant energy savings through VSA adjustments.

In summary, adjusting the VSA to 50°, 55°, 60°, 70°, and 80° results in substantial reductions in AEC by 11%, 11%, 11%, 9%, and 7%, respectively. To ascertain the optimal solution, a comprehensive assessment of the data is imperative. This evaluation should encompass both heating and cooling energy loads in conjunction with the AEC impact, necessitating a balanced approach.

Upon review of the provided data. illustrated in Table 6-2, VSA=60° emerges as the most promising solution. It achieves an impressive 11% reduction in annual energy consumption while concurrently minimizing both heating and cooling energy demands. This indicates a well-rounded approach that effectively balances heat retention with solar heat gain mitigation, thereby aligning with sustainable energy principles.

Table 6-2 Comparative analysis of heating, cooling, and annual energy consumption (AEC) across VSA scenarios.

	Heating		Cooling		AEC	
	[KWH]	**[%]**	**[KWH]**	**[%]**	**[KWH]**	**[%]**
Current State	1746.79		4473.02		6219.81	
VSA= 50°	2369.95	-36%	3145.24	30%	5515.19	11%
VSA= 55°	2320.30	-33%	3185.74	29%	5506.04	11%
VSA= 60°	2271.77	-30%	3268.50	27%	5540.28	11%
VSA= 70°	2155.43	-23%	3485.09	22%	5640.52	9%
VSA= 80°	2045.35	-17%	3714.89	17%	5760.24	7%

Overall, Figure 6-18 and Table 6-2 illustrates the significant impact of VSA adjustments on AEC in a primary school. The most notable reduction occurs at a VSA of 60°, as supported by comparative analysis depicted in Figure 6-19.

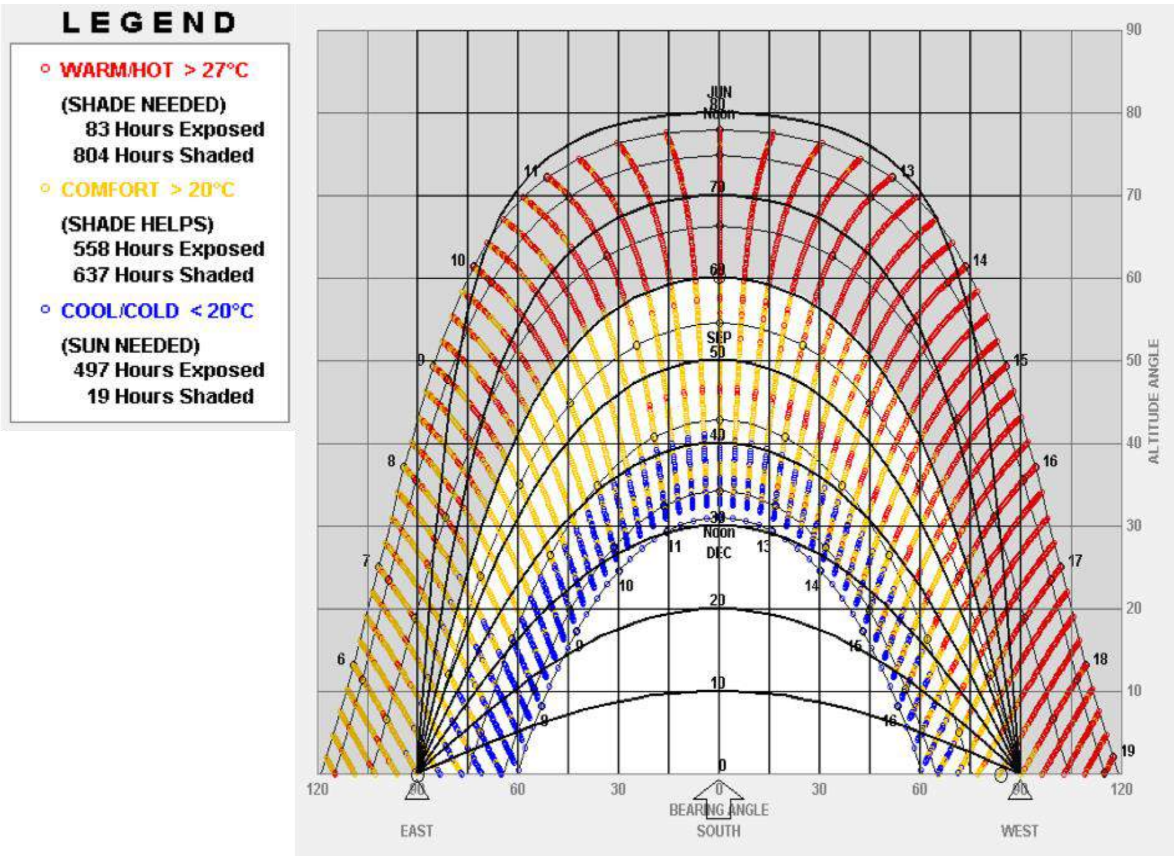


Figure 6-19 Sun shading chart in summer and fall of the studied region: Effect of VSA

6.2.2.3 Comparison of present results with previous studies

Upon comparing the results of our study with the findings from existing research, particularly the investigations conducted by Al Touma and Ouahrani [330], Alwetaishi et al. [249], Ghosh and Neogi [331], and Buratti et al. [250], notable similarities and distinctions emerge regarding the impact of shading devices on energy consumption and thermal comfort in educational buildings. While our study primarily focused on analyzing the effects of VSA adjustments on energy usage and indoor temperature regulation, the aforementioned research papers explored a broader range of factors, including various shading strategies, window-to-wall ratio, window positioning, and glazing systems. Interestingly, like Al Touma and Ouahrani [330] and Alwetaishi et al. [249], our findings underscored the significant role of shading devices, particularly vertical shading systems, in reducing energy consumption and enhancing thermal comfort. However, unlike Ghosh and Neogi [331] and Buratti et al. [250], who also emphasized the importance of window positioning and glazing systems, our study concentrated solely on the influence of VSA adjustments. Therefore, while our research provides valuable insights into the specific impact of VSA on energy efficiency and thermal comfort, future studies could explore the synergistic effects of shading devices, window design, and building orientation to optimize environmental performance in educational buildings further.

6.2.2.4 Recapitulation and Concluding Insights

The strategic orientation of VSA plays a vital role in optimizing solar shading strategies for the school building. It aligns with the sun's path to minimize direct sunlight penetration, mitigating solar heat gain and ensuring optimal thermal comfort and energy efficiency.

In conclusion, the study underscores the efficacy of VSA adjustments in influencing classroom temperatures, particularly in extreme summer conditions. Lower VSA values correlate with lower internal temperatures, highlighting the effectiveness of shading devices in enhancing thermal comfort. This insight informs decisions on shading strategies, emphasizing the crucial role of VSA in creating comfortable learning environments with reduced reliance on heating and cooling mechanisms.

6.2.3 Window-to-wall ratio

The WWR is a metric that expresses the proportion of a building's facade area occupied by windows compared to the total wall area. It is often used in architectural and energy efficiency assessments to analyze the impact of natural light and solar gain on a building's performance.

6.2.3.1 Thermal behavior:

The analysis of thermal behavior, as depicted in Figures 6-20 and 6-21, reveals that a WWR of 30% offers the most favorable thermal performance for Classroom 1 and Classroom 6 in the absence of heating and cooling systems. By contrasting various scenarios with different WWR values ranging from 20% to 50%, it becomes evident that WWR significantly influences internal temperatures. During winter, increasing WWR leads to a decrease in internal temperature, with Classroom 1 consistently exhibiting higher temperatures than Classroom 6. Conversely, in summer, higher WWR values result in elevated internal temperatures, particularly noticeable in Classroom 1. While Classroom 6 experiences similar trends, the differences are less pronounced. Overall, a WWR of 30% strikes a balance between insulation in winter and minimizing temperature rise in summer, ensuring acceptable thermal conditions in both classrooms during extreme weather conditions.

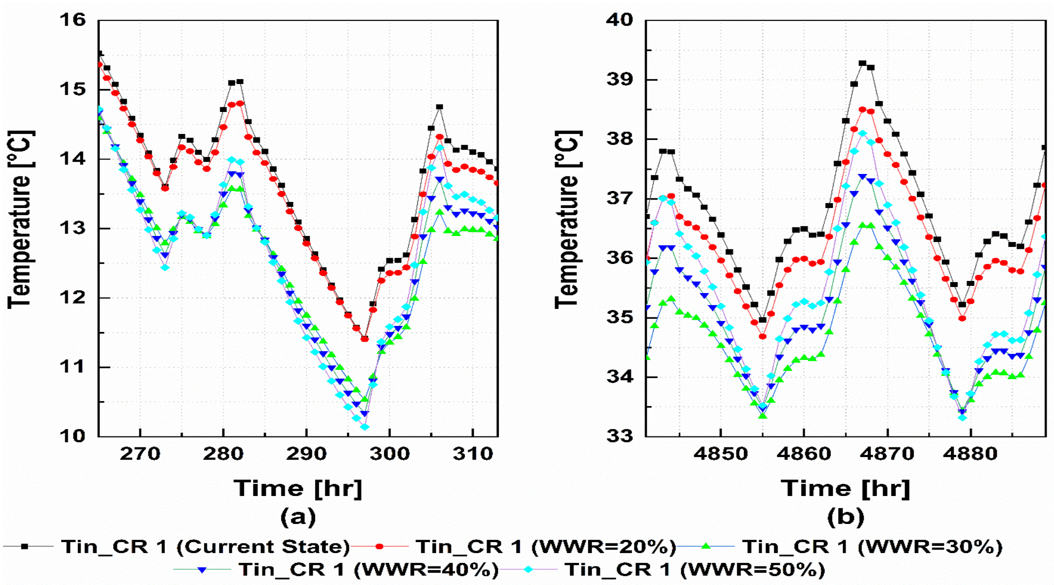


Figure 6-20 Comparison of internal temperature of classroom 1 in Winter (a) and Summer (b) for different Window-to-Wall Ratios (WWR)

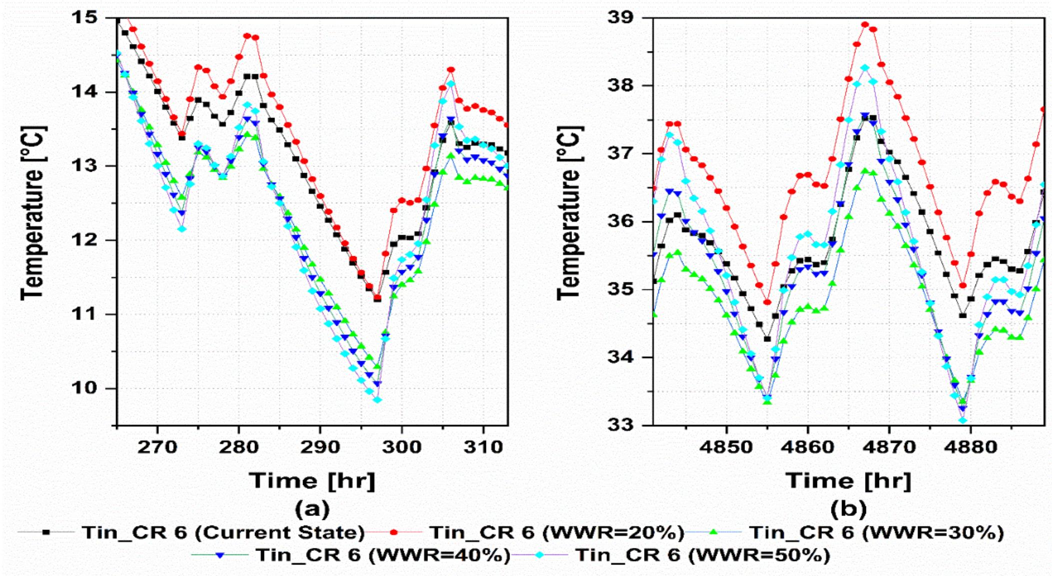


Figure 6-21 Comparison of internal temperature of classroom 6 in Winter (a) and Summer (b) for different Window-to-Wall Ratios (WWR)

6.2.3.2 Energetics behavior:

The comparison of heating and cooling requirements for Classroom 1 (CR_1) and Classroom 6 (CR_6) reveals a direct relationship with the WWR, as illustrated in Figure 6-22. Increasing WWR from 20% to 50% amplifies annual heating demands, with the highest requirements observed at 50%, representing a significant increase of 51% for CR_1 and 43% for CR_6 compared to the current state. Conversely, decreasing WWR leads to notable reductions in cooling demands, particularly evident at a 30% WWR, where CR_1 achieves a substantial 37% reduction compared to the current state. This trend is mirrored in the combined heating and cooling requirements, emphasizing the optimal efficiency of a 30% WWR, resulting in a 19% decrease for CR_1 and 4% for CR_6 relative to the current state. The subsequent analysis of ACE in Figure 6-23 reaffirms the superiority of the 30% WWR scenario, showcasing an 11% reduction in energy consumption compared to the current state. Thus, it is conclusive that a 30% WWR offers the most energy-efficient solution for the primary school, ensuring significant energy savings while maintaining suitable indoor conditions.

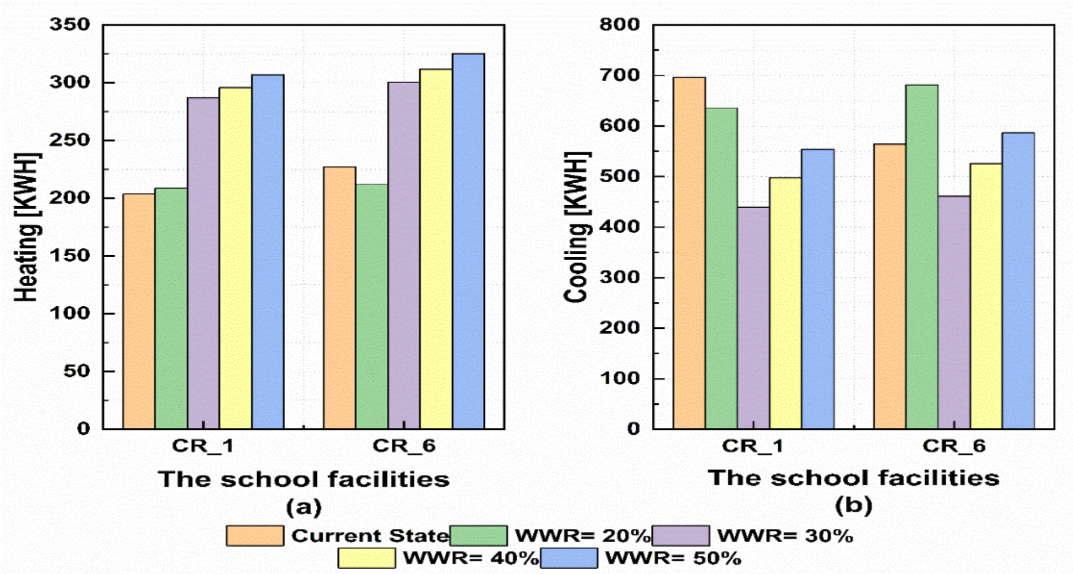


Figure 6-22 Energy loads of classrooms 1 and 6; (a): Heating, (b): Cooling

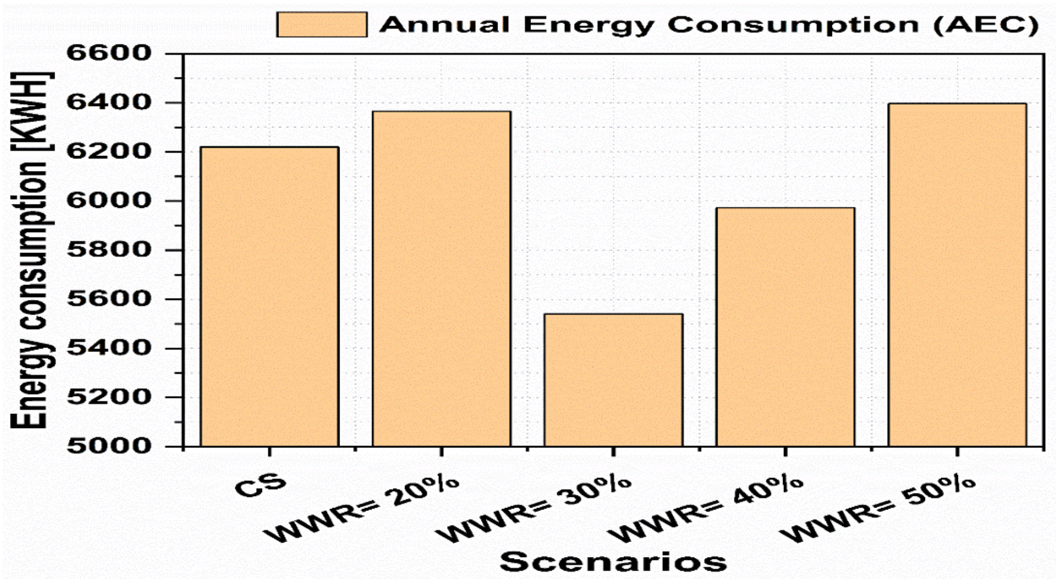


Figure 6-23 Impact of WWR on primary school annual energy demand

6.2.3.3 Comparison of present results with previous studies

Comparing the findings of my research with the recent studies regarding the WWR reveals notable similarities and differences in optimizing energy performance through building envelope design. Alaidroos and Krarti [332] investigated optimal residential building envelope systems in Saudi Arabia, determining significant energy savings ranging from 22.7% to 47.3% for different climate zones with varying WWR configurations. Similarly, Alwetaishi [253] emphasized the impact of WWR on thermal comfort in different climatic regions, recommending a WWR of 10% in hot and dry climates and 20% in moderate climates. This aligns with the findings of my study, which also highlights the critical role of WWR in energy performance optimization. Furthermore, Obrecht et al. [333]explored the influence of orientation on optimal glazing size, emphasizing the importance of WWR adjustments for different orientations and climates. Similarly, Alwetaishi and Taki [334] focused on the energy performance of school buildings in a hot climate, recommending specific WWR limitations based on orientation to minimize solar heat gain. Hashem Alqahtani and Eldeen Elgizawi [335] investigated the effect of openings ratio and wall thickness on energy performance in educational buildings, concluding that optimal energy savings were achieved with specific WWR configurations and wall materials. Overall, these studies collectively underscore the importance of considering WWR as a critical factor in optimizing energy efficiency and thermal comfort in building design, reinforcing the significance of my research findings in this domain.

6.2.3.4 Recapitulation and Concluding Insights

Based on a comprehensive analysis of these findings, it can be concluded that a window-to-wall ratio of 30% provides the most energy-efficient solution for the elementary school. This ratio results in substantial energy savings while preserving a suitable indoor environment. When making a final decision, it is essential to consider additional factors such as insulation, climate conditions, and energy systems.

6.2.4 Glazing

Glazing refers to the installation of glass or transparent materials in windows, doors, or other openings in a building. Glazing plays a crucial role in providing natural light, views, and sometimes ventilation. It can also influence a building's energy efficiency and thermal performance, as different types of glazing materials and coatings have varying properties related to heat gain, insulation, and UV protection.

6.2.4.1 Thermal behavior

The thermal behavior analysis, as illustrated in Figures 6-24a and 6-25a, indicates that all glazing panel types (Double, Double-Low E, and Triple) result in higher internal temperatures in Classrooms 1 and 6 compared to the current state during extreme winter conditions. This suggests a potential improvement in thermal performance and winter comfort by replacing the existing glazing panels with any of the studied types. Moreover, a progression from single to triple glazing shows an increase in internal temperature, implying improved insulation and heat retention with additional glazing layers. In summer, Figures 6-24b and 6-25b demonstrate that Double Low Emissivity glazing exhibits lower temperatures compared to other types, indicating reduced heat gain from outside and enhancing thermal comfort during hot seasons. Overall, Double Low Emissivity (Double-Low E) glazing offers superior thermal performance in both winter and summer, contributing to enhanced energy efficiency and classroom comfort.

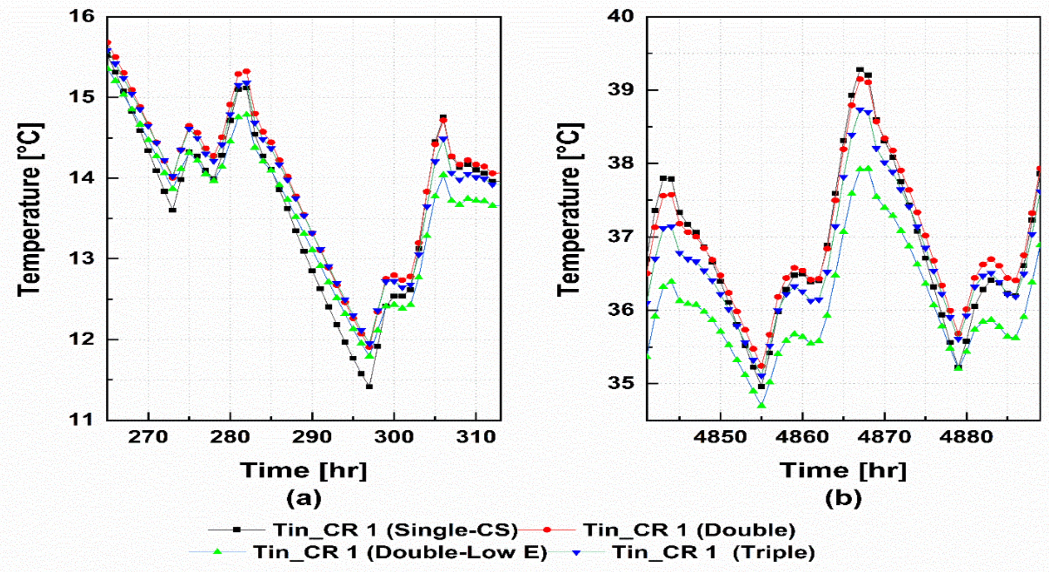


Figure 6-24 Comparison of internal temperature in classroom 1 with different types of glazing during Winter (a) and Summer (b)

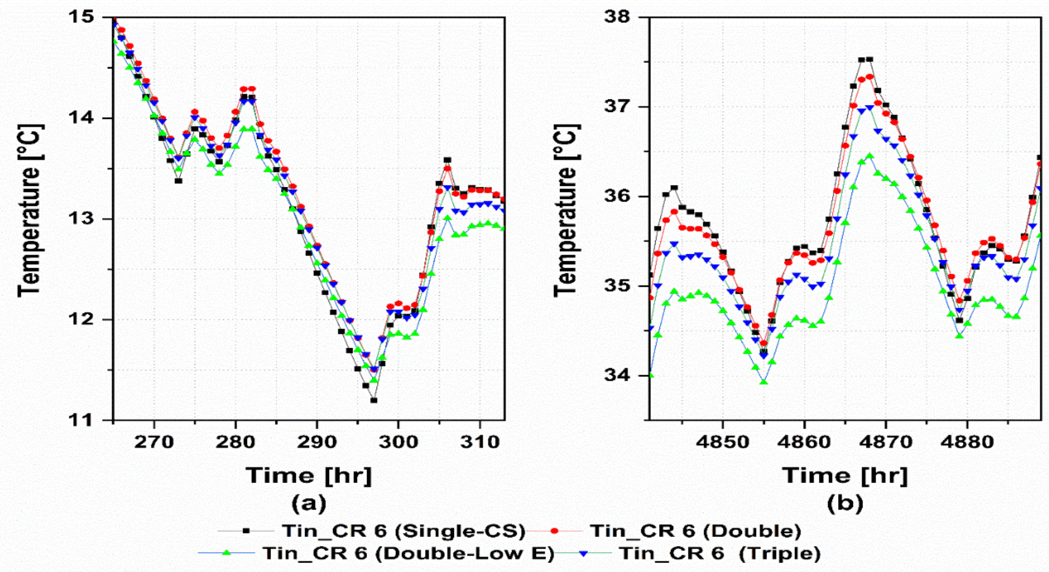


Figure 6-25 Comparison of internal temperature in classroom 6 with different types of glazing during Winter (a) and Summer (b)

6.2.4.2 Energetics behavior

The energetics behavior analysis focuses on assessing the influence of different window glazing configurations on the heating and cooling performance of classrooms 1 and 6. Figures 6-26 and 6-27 provide a detailed overview of the findings. Regarding heating energy consumption (Figure 6-26a), double, double low-emissivity, and triple glazing options result in energy savings ranging from 8% to 15% for classroom 1, and from 4% to 9% for classroom 6 compared to single glazing (current state). Similarly, in terms of cooling energy consumption (Figure 6-26b), the alternative glazing options led to reductions ranging from 6% to 20% for classroom 1 and 6% to 18% for classroom 6. Notably, double low-emissivity glazing consistently demonstrates the most significant energy savings across both heating and cooling aspects. Figure 6-27 further highlights the impact of glazing upgrades on the annual energy demand of the primary school, with double low-emissivity glazing offering the highest energy efficiency, reducing consumption by up to 14% compared to single glazing. In summary, the analysis underscores the substantial benefits of transitioning from single to double, double low-emissivity, or triple glazing, with double low-emissivity glazing emerging as the optimal choice for enhancing both thermal behavior and energy performance in the studied classrooms.

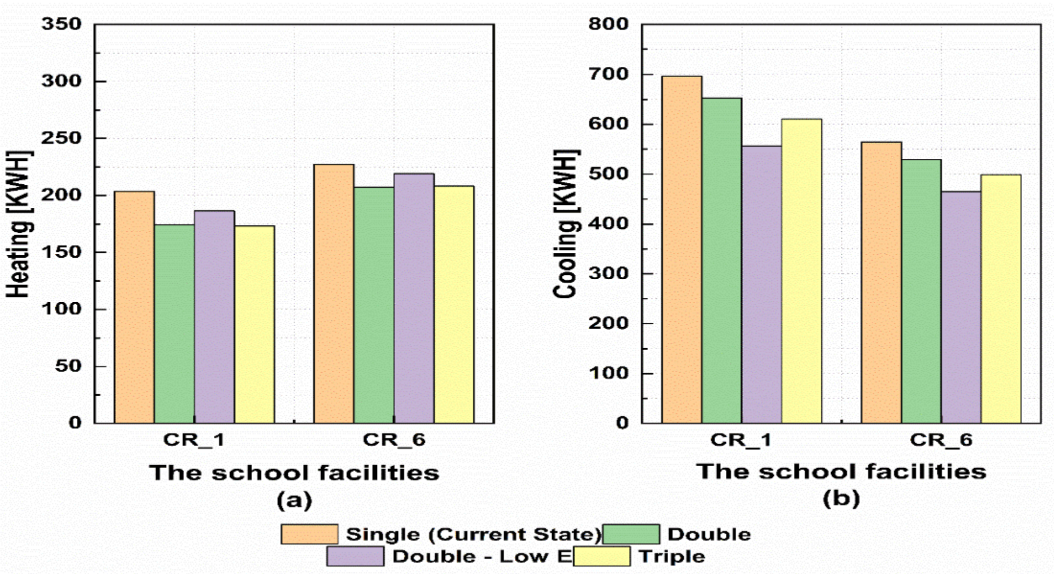


Figure 6-26 Energy loads comparison of classrooms 1 and 6 with different window glazing scenarios for Heating (a) and Cooling (b)

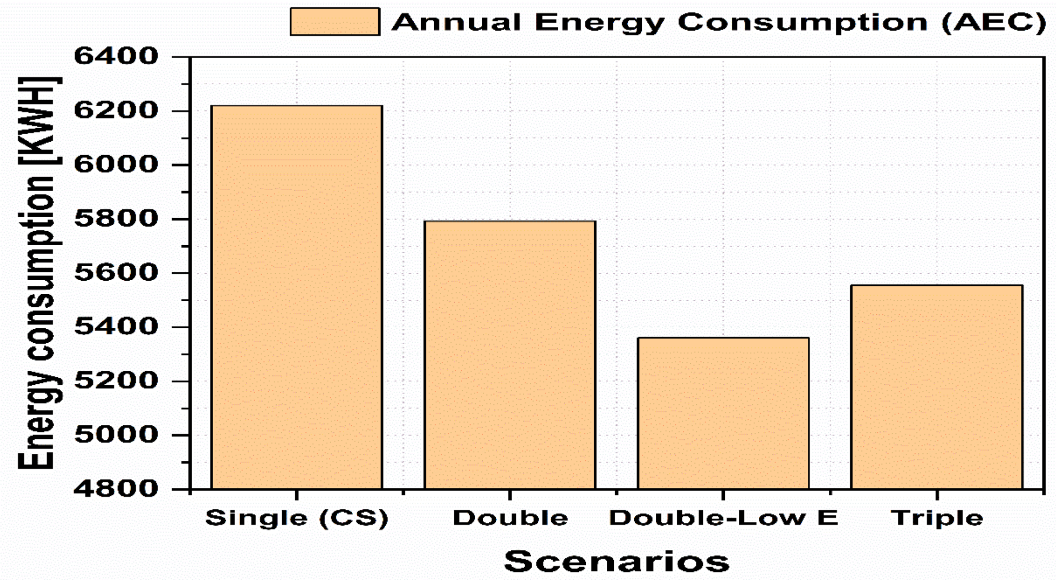


Figure 6-27 Impact of window glazing scenarios on primary school annual energy demand

6.2.4.3 Comparison of present results with previous studies

Comparing the findings of my research with relevant studies regarding glazing solutions reveals several key insights. In the study by Somasundaram et al. [336], the retrofit double-glazing solution with low-E coating demonstrated notable energy savings ranging from 3% to 9%, depending on the existing glazing type and area. Similarly, in the investigation by Somasundaram et al. [337], retrofitting low-e-based double glazing resulted in substantial HVAC energy savings, particularly for east and west-facing facades, reaching up to 5.9%. These findings align with the outcomes of the research conducted by Almarzouq and Sakhrieh [312], which emphasized the significant energy-saving potential (up to 24.7%) achievable by replacing single-glazing windows with double-Low E glazing windows. Furthermore, Abdelhakim et al. [275] highlighted the importance of glazing configurations in optimizing daylight performance and visual comfort in classrooms, recommending specific glazing patterns and window-to-wall ratios to maximize useful daylight illuminance while minimizing visual discomfort. Similarly, Buratti et al. [250] emphasized the effectiveness of external shading devices, Low-E glazing systems, and optimal building orientation in reducing energy consumption in primary school buildings. These studies collectively underscore the significant role of glazing solutions, such as low-E retrofit double glazing, in enhancing energy efficiency and thermal comfort in educational facilities, providing valuable insights for sustainable building design in various climatic contexts.

6.2.5 Building envelope adjustments

To enhance the building envelope, we are making modifications by creating new areas adjacent to the classrooms on both the Western and Eastern sides, as depicted in Figure 6-28. The main goal is to evaluate how changes in the WWR impact the indoor conditions of classrooms and energy usage.

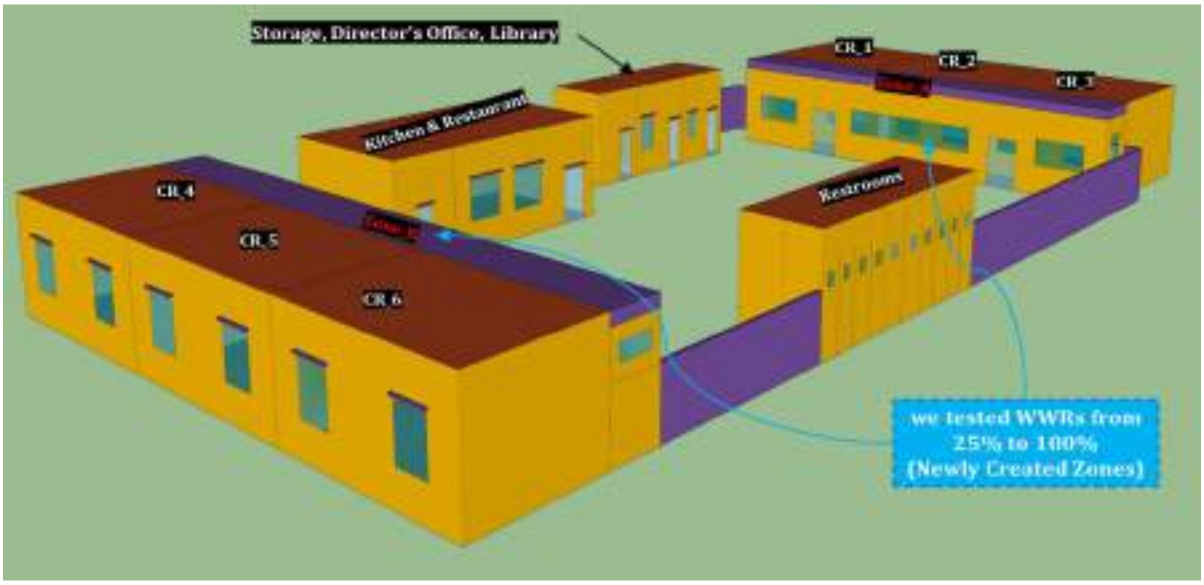


Figure 6-28 Building envelope adjustments showing newly added spaces on the Western and Eastern sides of the classrooms

6.2.5.1 Thermal behavior

This section delves into the thermal behavior analysis of classrooms 1 and 6, considering extreme winter and summer conditions alongside varying WWR scenarios. Internal temperatures (Tin) were assessed at the current state (CS) and WWR percentages of 100%, 75%, 50%, and 25%, as depicted in Figures 6-28 and 6-29.

During winter analysis, both classrooms exhibited higher indoor temperatures with decreasing WWR, indicating reduced heat loss through smaller window areas. Notably, a WWR of 50% facilitated a balanced environment with moderate temperatures, promoting comfortable learning conditions for students and teachers alike. Conversely, in summer, larger windows led to higher indoor temperatures, with the greatest heat gain observed at a WWR of 100%. Decreasing WWR resulted in cooler indoor temperatures, with a WWR of 25% offering the lowest readings. Interestingly, a WWR of 50% consistently maintained a balanced indoor temperature, fostering a conducive learning environment throughout summer.

Overall, a WWR of 50% emerged as the optimal choice for both classrooms, ensuring a harmonious blend of thermal insulation and natural light exposure, thereby enhancing interior comfort. This ratio consistently maintained temperature equilibrium across all seasons, underscoring its efficacy in promoting favorable learning environments in primary schools.

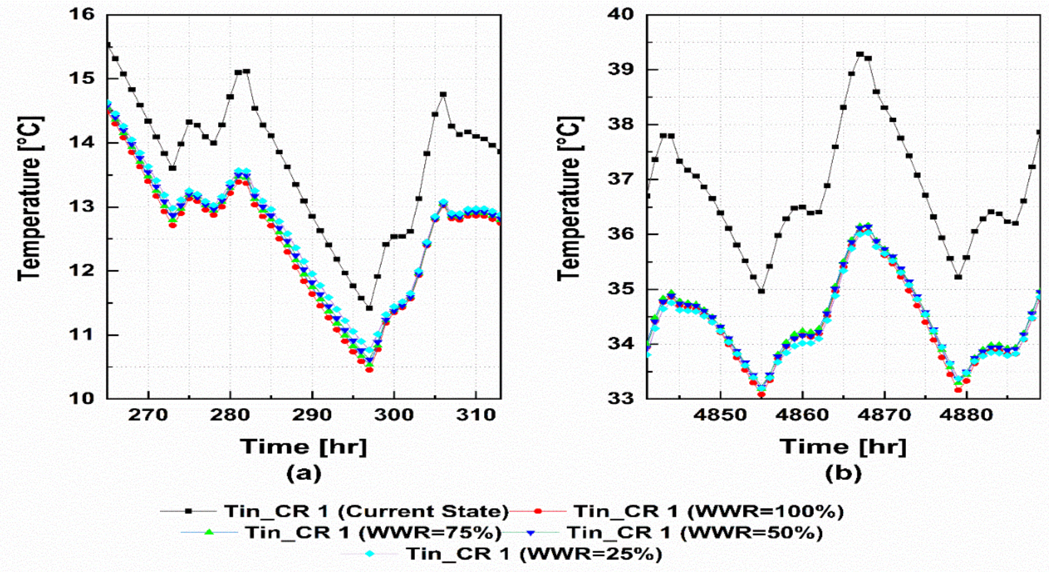


Figure 6-29 Indoor temperatures of classrooms 1: Impact of WWR on Winter (a) and Summer (b)

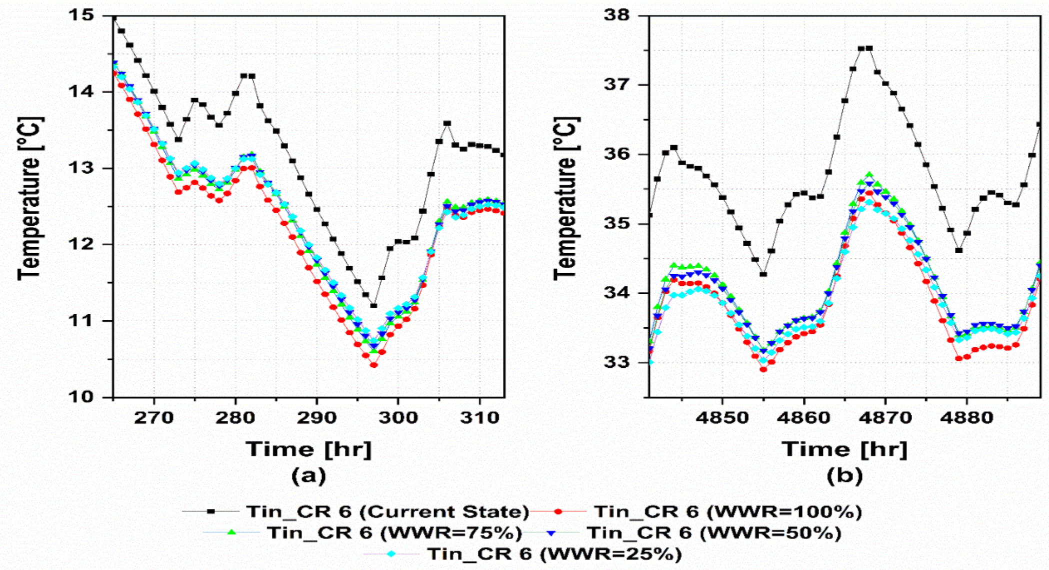


Figure 6-30 Indoor temperatures of classrooms 6: Impact of WWR on Winter (a) and Summer (b)

6.2.5.2 Energetics behavior

This section investigates the energy performance of classrooms 1 and 6, focusing on the impact of varying WWR on energy consumption. The analysis compares the current state of the primary school to scenarios with WWR percentages of 100%, 75%, 50%, and 25%, as illustrated in Figure 6-30.

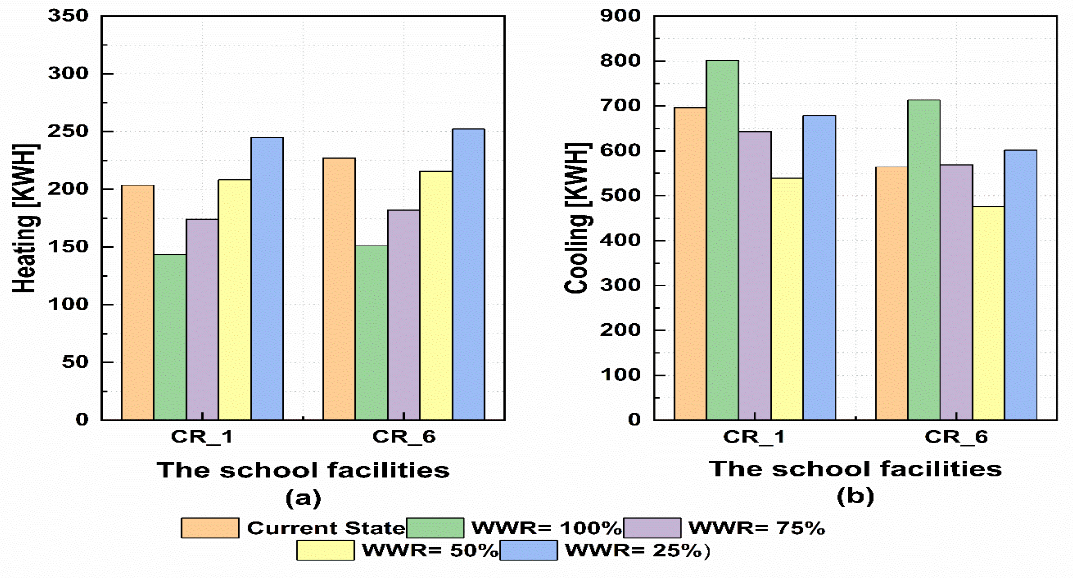


Figure 6-31 Impact of WWR on energy loads of classrooms 1 and 6 for heating and cooling

Annual heating energy consumption analysis (Figure 6-30a) reveals that a WWR of 50% consistently yields the lowest heating demand for both classrooms. Reduced heat loss through smaller window areas at 50% WWR enhances thermal insulation, leading to substantial winter energy savings. Conversely, a WWR of 25% results in increased heating demand due to limited natural light and ventilation. Similarly, the evaluation of annual cooling energy consumption (Figure 6-30b) demonstrates that a WWR of 50% provides the most energy-efficient cooling scenario for both classrooms. Balanced daylighting and improved thermal insulation minimize heat gain, reducing summertime cooling requirements. Conversely, a WWR of 25% leads to heightened cooling needs, negatively impacting overall energy performance.

Figure 6-31 presents a comprehensive overview of the annual energy loads for all school facilities, highlighting the impact of various WWR percentages on total energy demand. Results indicate that a WWR of 50% significantly reduces annual energy consumption by 12% compared to the current state, owing to the optimal balance between thermal insulation and natural light exposure. Conversely, 100% and 25% WWR scenarios result in less energy-efficient outcomes, with 6% and 4% increases in energy consumption, respectively.

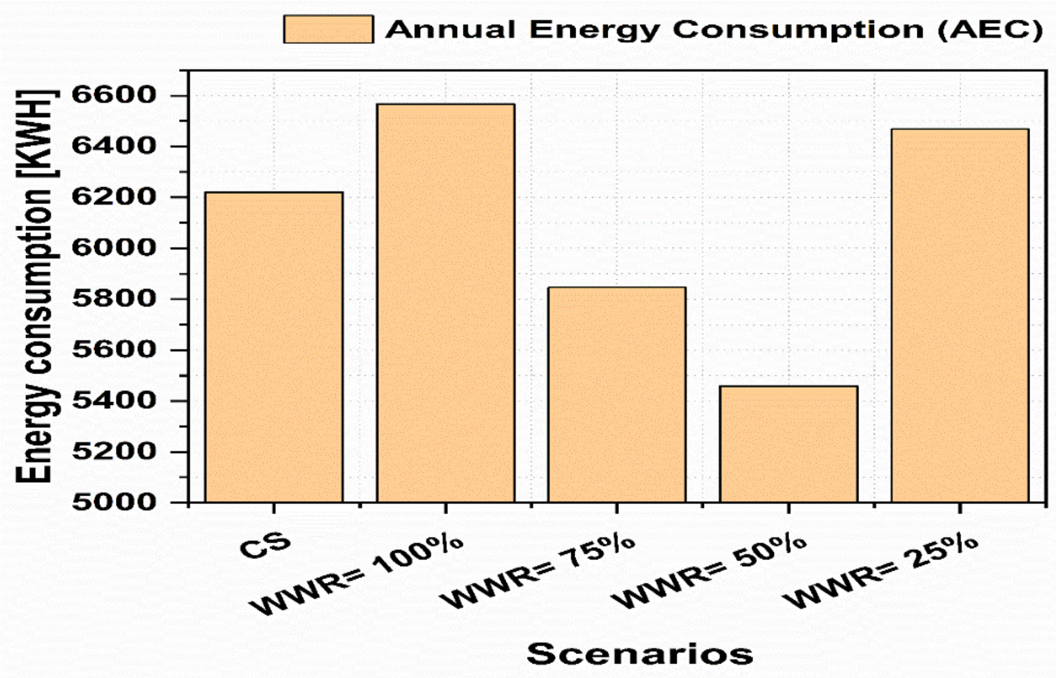


Figure 6-32 Effect of WWR scenarios on primary school annual energy demand

In conclusion, a WWR of 50% emerges as the most energy-efficient scenario, offering substantial energy savings and balanced thermal performance throughout the year. It is recommended to prioritize a WWR of approximately 50% in classroom window design to optimize energy efficiency and foster a conducive learning environment for students. Further research and simulations may validate these findings and explore additional strategies for enhancing classroom thermal performance.

The interplay between WWR and glazing types significantly influences a building's energy efficiency and thermal behavior. WWR denotes the window area relative to the building envelope, while glazing types encompass glass characteristics such as insulation and solar heat gain. These factors are pivotal in shaping the energy performance and comfort levels of educational facilities.

6.2.6 Optimum model of the primary school

Drawing on chosen passive strategies, including external shading devices, WWR, glazing types, and modifications to the building envelope, this section will strive to identify the optimal model for the primary school.

The "optimum model" of the primary school involves finding a balanced combination of WWR and glazing types that maximizes energy efficiency and thermal comfort. The aim is to strike a harmonious equilibrium between natural light, insulation, and solar heat gain.

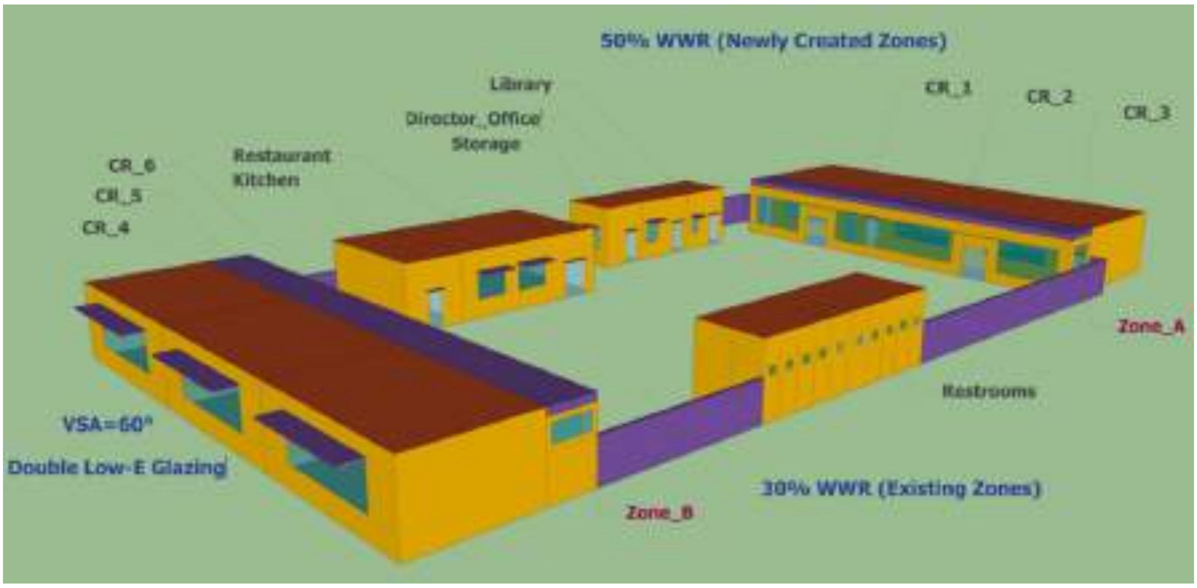


Figure 6-33 A 3D schematic of optimized primary school model

This 3D schematic illustrates the optimized primary school model based on the most effective design choices from various energy efficiency scenarios.

Key optimizations include a 60° VSA, a 30% WWR for existing zones, Double Low-E glazing, and a 50% WWR for the newly created zones.

These changes were implemented to enhance energy efficiency and thermal comfort throughout the building, as depicted in Figure 6-32.

6.2.6.1 Thermal behavior

During the winter analysis, Classroom 1 and Classroom 6 were assessed for their thermal performance in both the current state and an optimized model; key optimizations include a 60° VSA, a 30% WWR for existing zones, Double Low-E glazing, and a 50% WWR for the newly created zones. Figures 6-33a and 6-34a presented the findings, indicating a marginal superiority in internal temperatures for the current state compared to the optimized model. Classroom 1 exhibited a 1.5°C difference, while Classroom 6 showed a 1.2°C difference.

Extending the analysis to summer, Figures 6-33b and 6-34b showcased significant temperature improvements in the optimized model for both classrooms. Classroom 1 experienced a remarkable 4°C difference, while Classroom 6 showed a 3°C improvement compared to the current state. Passive cooling strategies led to notably lower internal temperatures, enhancing the summer learning environment by 3°C to 4°C in both classrooms. These results highlight the efficacy of passive cooling strategies in reducing heat gain and ensuring comfortable indoor conditions during hot weather.

In summary, while the current state may have an advantage in winter, the optimized model demonstrates superior thermal performance, particularly in summer. By effectively mitigating heat loss in winter and heat gain in summer, the optimized model ensures stable and comfortable indoor temperatures throughout the year. This aligns with sustainability goals by reducing reliance on energy-intensive cooling systems and promoting energy efficiency in the primary school's facilities.

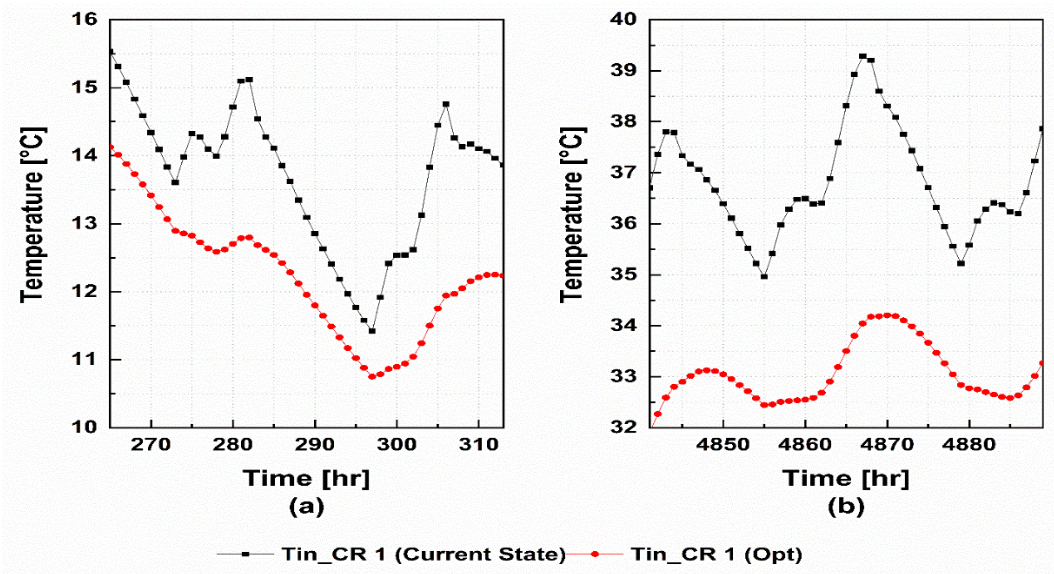


Figure 6-34 Internal temperature evaluation for classroom 1: Winter (a) and Summer (b)

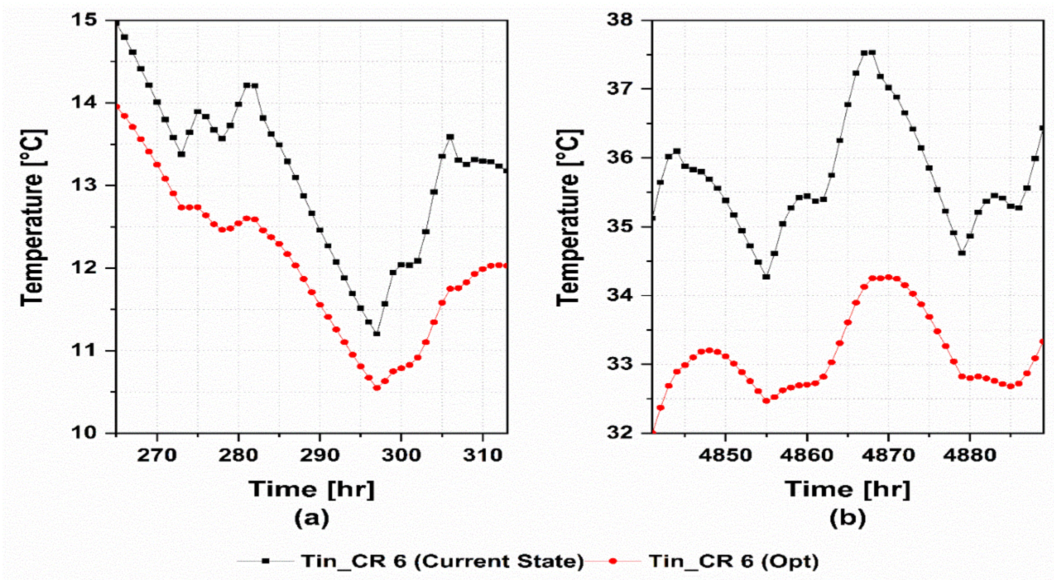


Figure 6-35 Internal temperature evaluation for classroom 6: Winter (a) and Summer (b)

6.2.6.2 Energetics behavior:

In this section, the energy behavior of the primary school was analyzed by comparing its current state to the optimized model after the implementation of specific passive strategies. Figure 6-35 illustrates the annual heating and cooling loads for each facility in both scenarios.

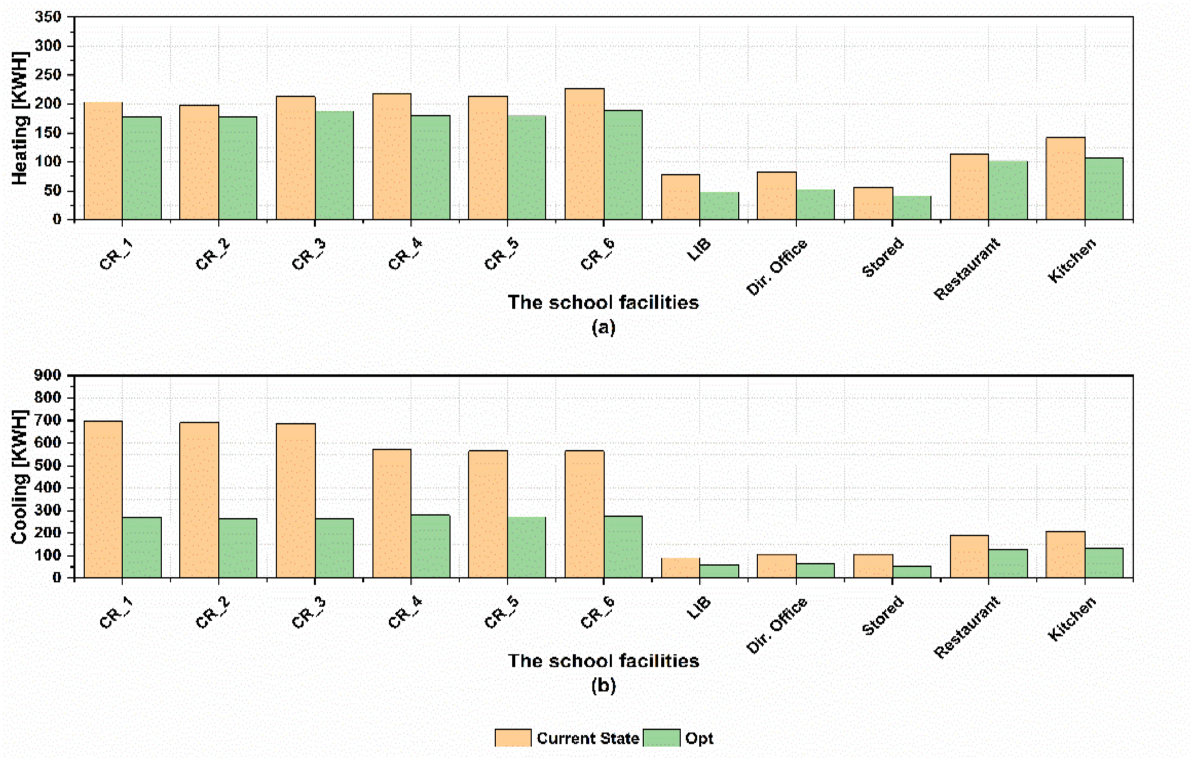


Figure 6-36 Annual heating and cooling needs for each facility: Comparison between the current state and optimized model with passive strategies

In Figure 6-35a, annual heating requirements show consistent reductions across all facilities in the optimized model compared to the current state. For instance, Classroom 1 (CR_1) saw a notable decrease from 203.54 kWh to 178.8 kWh, demonstrating improved heating efficiency. Overall, reductions ranged from 9% to 18%, with CR_2 and CR_5 experiencing the greatest decreases. These results underscore the effectiveness of passive strategies in enhancing energy efficiency and reducing heating demands in primary school buildings.

Figure 6-35b demonstrates substantial reductions in annual cooling requirements for the optimized model compared to the current state. For example, Classroom 1 (CR_1) showed a remarkable decrease from 696.11 kWh to 271.41 kWh, representing a significant improvement in energy conservation. Overall, cooling requirements decreased by approximately 61% to 69% across various facilities, with CR_1, CR_3, CR_4, and CR_6 showing the most significant improvements. These findings highlight the efficacy of passive strategies in mitigating cooling demands and promoting energy efficiency, particularly during warm periods.

The analysis further elucidates nuanced variations in heating demands across different spaces within the primary school, influenced by factors like thermal mass, insulation, and orientation. While some areas experienced significant reductions, localized increases may occur due to architectural and environmental factors. However, this contextual understanding resolves discrepancies in the data, offering a comprehensive view of how passive techniques affect different spaces in the school.

Figure 6-37 underscores the substantial impact of passive strategies on the primary school's annual energy demand. A notable reduction of 2,716.00 kWh, representing a 44% decrease in energy demand for the optimized model compared to the current state, demonstrates the effectiveness of passive strategies in enhancing energy efficiency and promoting sustainability. This reduction includes a 17% decrease in heating demand and a remarkable 54% decrease in cooling demand, highlighting the positive effects of passive strategies on energy consumption optimization and environmental responsibility within the school facility.

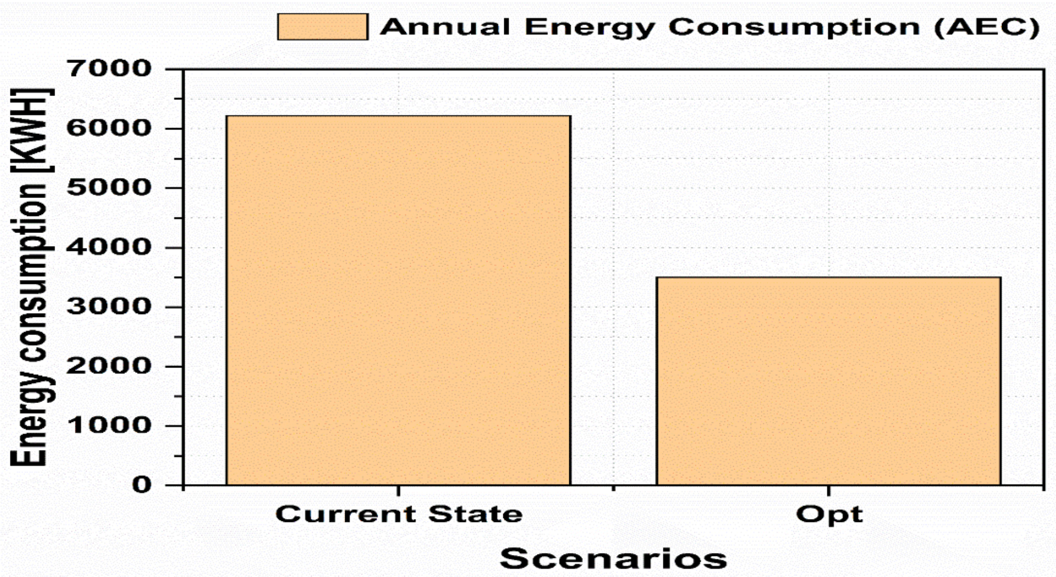


Figure 6-37 Impact of passive strategies on annual energy demand

The analysis concludes by highlighting the significant improvements in energy efficiency achieved by the optimized model, which incorporates selected passive strategies for heating and cooling demands, surpassing the performance of the current state. The implementation of these passive strategies reduces energy consumption, making the primary school's operations more sustainable and environmentally friendly. The study highlights the importance of integrating passive strategies into building design in order to achieve significant energy savings and improve the overall performance of educational facilities. Notably, the optimized model demonstrates significant reductions in both heating and cooling demands, highlighting the positive impact of passive strategies on the energy performance and sustainability of the school. The research demonstrates conclusively that the optimized model outperforms the current state, providing superior energy efficiency and thermal comfort. Significantly less energy consumption indicates potential cost-saving benefits for the Primary school and highlights the model's contribution to environmental conservation. This analysis validates the efficacy of passive strategies as a viable strategy for optimizing energy behavior and promoting sustainable building practices in educational institutions.

In the context of the primary school, the optimum model would likely involve a WWR that allows for sufficient daylighting without compromising insulation. Additionally, the selection of glazing types, such as double low emissivity (Double-Low E) glass, can contribute to reducing heat transfer while maintaining good visibility and daylight penetration.

The optimal model seeks to minimize the energy consumption of the building for heating and cooling while ensuring a comfortable indoor environment for occupants. It is a result of a thorough analysis of the interactions between WWR and glazing types through simulations and assessments, aiming to achieve the best possible balance for the specific climatic conditions and functional requirements of the primary school.

7 Conclusions and Future Research

In conclusion, this doctoral thesis has elucidated the critical role of passive strategies in enhancing the energy efficiency and thermal comfort of buildings within Mediterranean climates, focusing specifically on the province of Ain Temouchent, Algeria. Through two distinct yet interrelated studies, significant insights have been gleaned regarding the optimization of energy performance in both residential and educational buildings.

The findings from the study on traditional houses in the Mediterranean region, specifically in Ain Temouchent, Algeria, aimed to assess the efficacy of insulation materials and glazing options in enhancing energy efficiency and indoor comfort. Through rigorous theoretical analysis and simulation using TRNSYS 17 software, the research meticulously evaluated various insulation materials, including Expanded Polystyrene, Glass Wool, Rock Wool, and Wood Fiber, at different thicknesses. The findings underscored the superior thermal performance of wood fiber insulation, particularly when applied at a thickness of 9 cm, resulting in substantial energy savings and improved indoor comfort compared to conventional insulation materials. Additionally, the study highlighted the significant impact of glazing configurations on building energy performance, with double glazing emerging as the most effective option for maintaining comfortable indoor temperatures throughout the year. Transitioning from single to double glazing was found to lead to notable reductions in heating and cooling loads, underscoring the importance of appropriate glazing choices in achieving energy efficiency.

Moreover, the simulations conducted revealed valuable insights into the energy-saving potential of insulation and glazing options, demonstrating energy savings ranging from 4-6% for heating and 1-2% for air conditioning when utilizing wood fiber insulation with a thickness of 9 cm. These findings not only provide practical guidance for architects and engineers involved in building design but also offer compelling reasons for policymakers to prioritize energy-efficient building practices. Despite the study's limitations, such as its focus on insulation and glazing and neglect of factors like humidity and air movement, it serves as a crucial step towards optimizing building energy performance in Mediterranean climates, paving the way for future research to explore broader factors affecting building performance and design optimization.

Similarly, in this comprehensive study focused on primary school classrooms within the

Mediterranean climate of Khoualed Abdel Hakem, Ain Temouchent Wilaya, Algeria, a meticulous exploration of passive strategies has been undertaken. The study highlights the effectiveness of passive design strategies such as external shading devices, Window-to-Wall Ratio, glazing type, and building envelope adjustments. Through an exhaustive analysis, encompassing external shading devices, Window-to-Wall Ratio (WWR) adjustments, glazing types, and building envelope modifications, the research elucidates critical insights into optimizing the energy performance of educational facilities. Notably, the investigation into Vertical Shading Angle (VSA) emphasizes the efficacy of a 60° setting, yielding an 11% reduction in Annual Energy Consumption (AEC) and highlighting sustainable energy savings over time. Similarly, the study underscores the significance of a 30% WWR ratio, showcasing an 11% reduction in AEC, thereby emphasizing the imperative of meticulous consideration in design decisions. Furthermore, the analysis of diverse glazing scenarios underscores the superiority of Double Low Emissivity (Double-Low E) glazing, showcasing a remarkable 14% reduction in AEC, reaffirming the pivotal role of thoughtful glazing choices in sustainable school building design.

Moreover, the study reveals that building envelope adjustments, coupled with a recommended WWR of 50%, consistently achieve a balanced thermal environment, effectively optimizing heating retention in winter and mitigating heat gain in summer. This prudent choice significantly diminishes heating and cooling demands, culminating in a noteworthy 12% reduction in the primary school's total energy demand. Consequently, the amalgamation of these individual optimizations culminates in the assessment of the primary school's optimum model, boasting a remarkable 44% overall reduction in energy consumption. This optimized model not only ensures comfortable thermal conditions but also adeptly harnesses passive cooling strategies, aligning with sustainability objectives and curbing reliance on energy-intensive cooling systems. In essence, the study fervently advocates for the integration of passive design principles in educational facilities, heralding a new era of energy-conscious and environmentally responsible practices in school building design. While the study provides valuable insights, acknowledging certain limitations, including its geographical specificity and the exclusive focus on passive solutions, it lays the groundwork for future investigations to delve deeper into the economic viability and user-centric aspects of sustainable school design, thereby reinforcing the imperative for energy-efficient and user-friendly educational infrastructures.

While the research presented in this thesis provides valuable insights into enhancing building energy performance in Mediterranean climates, several avenues for future research emerge. Firstly, comprehensive studies could be conducted to examine the long-term performance and durability of chosen materials across varying climates and building designs, considering factors such as humidity, air movement, and occupant behavior. Additionally, the economic viability of passive strategies warrants further investigation, including cost-benefit evaluations and life-cycle assessments to inform decision-making processes. Furthermore, the integration of active systems with passive solutions presents an opportunity for synergistic energy savings and warrants exploration in subsequent studies. Lastly, incorporating occupant feedback and behavior patterns into building design considerations would enhance the user-friendliness and effectiveness of sustainable building solutions.

In essence, the research conducted in this thesis contributes to the advancement of knowledge in sustainable building design and energy efficiency, offering practical insights for architects, engineers, and policymakers. By advocating for the adoption of passive strategies and promoting ecologically responsible practices, this research endeavors to address the challenges of climate change and energy sustainability in Mediterranean climates and beyond.

8 Appendix

8.1 Appendix I: Building Design and Analysis software

Building energy modeling codes are invaluable tools for estimating various aspects of a building's energy performance. They can be utilized to assess energy consumption, HVAC system sizing, lighting requirements, and the economic feasibility of energy efficiency measures. Additionally, these codes serve as guiding tools for building designers to develop optimal energy-efficient designs and predict cost-effective energy efficiency retrofits for existing buildings. Developed by different groups, these modeling tools heavily rely on user input data, including building geometry, construction details, geographic location, mechanical equipment, and building type (residential or commercial), for accurate energy simulations.

Building design and analysis software plays a crucial role in modern architectural and engineering practices. These tools are essential for efficiently designing, simulating, and analyzing various aspects of buildings, ranging from their structural integrity and energy performance to their environmental impact and sustainability [112,336]. Among the most prevalent are:

8.1.1 Weather Software

Weather software, such as Meteonorm and Climate Consultant, are indispensable tools in architectural and engineering practices. They provide vital data and simulations for understanding local climate conditions, which are essential for designing energy-efficient and sustainable buildings. These software programs offer precise meteorological data, including solar radiation, temperature, humidity, and wind patterns, allowing designers and engineers to optimize building performance and occupant comfort while minimizing energy consumption and environmental impact [307,309].

8.1.1.1 Meteonorm

Meteonorm is a versatile meteorological analysis tool commonly used in architectural and engineering fields. It provides detailed climatic data such as solar radiation, temperature, and wind speed from meteorological stations worldwide. This enables accurate simulations and assessments for building design and energy efficiency strategies [307].

8.1.1.2 Climate Consultant

Climate Consultant is a tool for visualizing and analyzing climate data, aiding in building design and energy performance assessment. It offers interactive visualization of climate data, facilitating the evaluation of outdoor comfort conditions and passive design approaches.

Together, these software applications empower professionals to optimize building performance and sustainability by integrating climatic considerations into the design process [309].

8.1.2 3D Building Modeling Software

3D Building Modeling Software encompasses a range of tools used by architects, engineers, and designers to create detailed digital representations of buildings and structures. Among the most commonly utilized software in this category are:

8.1.2.1 AutoCAD Architecture

AutoCAD Architecture is a specialized version of AutoCAD tailored specifically for architectural design. It offers a comprehensive suite of tools for creating and documenting building designs, including 2D drafting, 3D modeling, and building information modeling (BIM) capabilities [339].

8.1.2.2 SketchUp

SketchUp is a user-friendly 3D modeling software widely used for architectural and interior design projects. It enables designers to quickly create conceptual models, generate realistic renderings, and visualize designs in 3D space. SketchUp's intuitive interface and extensive library of plugins make it a popular choice among architects and designers [340].

8.1.2.3 Revit Architecture

Revit Architecture is a BIM software developed by Autodesk, designed for architects, engineers, and construction professionals. It allows users to create detailed 3D models of buildings and manage building information throughout the design and construction process. Revit's parametric modeling capabilities enable dynamic design changes and seamless collaboration among project stakeholders [341].

8.1.2.4 Rhino

Rhino, or Rhinoceros, is a powerful 3D modeling software commonly used in architecture, industrial design, and digital fabrication. It offers flexible modeling tools for creating complex organic shapes, as well as precise geometric forms. Rhino's compatibility with various plugins and rendering engines makes it a versatile tool for architectural visualization and design exploration [342].

These software applications enable architects and designers to efficiently create, visualize, and analyze building designs in three dimensions, facilitating better communication, decision-making, and collaboration throughout the design process.

8.1.3 Building Energy Simulation Software

Building Energy Simulation Software comprises a suite of tools used to assess and optimize the energy performance of buildings through computer-based modeling and analysis. Key software programs in this category include:

8.1.3.1 TRNSYS (TRaNsient SYstem Simulation Program)

TRNSYS is a transient simulation software widely used for modeling renewable energy systems, HVAC systems, and building energy performance. It offers a flexible modular structure that allows users to build custom simulations by combining predefined components and models to analyze complex energy systems and evaluate design alternatives [310,350].

8.1.3.2 EnergyPlus

EnergyPlus is a robust simulation engine developed by the U.S. Department of Energy (DOE) for modeling building energy consumption and performance. It allows users to simulate the dynamic thermal and energy behavior of buildings, HVAC systems, and renewable energy technologies to evaluate energy efficiency measures and design strategies [343].

8.1.3.3 OpenStudio

OpenStudio is an open-source software platform developed by the National Renewable Energy Laboratory (NREL) for building energy modeling and analysis. It provides a user-friendly interface and powerful simulation capabilities for architects, engineers, and researchers to assess energy efficiency measures, compare design options, and comply with energy codes and standards [344].

8.1.3.4 DesignBuilder

DesignBuilder is a comprehensive energy modeling software that integrates 3D building modeling with advanced energy simulation capabilities. It enables architects, engineers, and energy consultants to perform detailed analyses of building energy use, daylighting, thermal comfort, and HVAC system performance to optimize building design and operation.

These software tools enable building designers, energy consultants, and researchers to simulate and analyze the energy performance of buildings under various operating conditions, evaluate the effectiveness of energy-saving measures, and make informed decisions to achieve energy efficiency goals and sustainability objectives [345].

8.1.3.5 eQuest

eQuest, short for Quick Energy Simulation Tool, is a powerful building energy modeling software developed by the U.S. Department of Energy (DOE) for analyzing the energy use and performance of new and existing buildings. It offers advanced simulation capabilities for assessing energy-saving measures, conducting energy audits, and optimizing building systems to achieve energy efficiency goals and comply with energy codes and standards.

8.1.4 Building Lifecycle Assessment Software

Building Lifecycle Assessment (LCA) Software is essential for evaluating the environmental impact of buildings throughout their entire lifecycle, from raw material extraction and manufacturing to construction, operation, and end-of-life disposal or recycling [346]. Two prominent software programs in this category are:

8.1.4.1 SimaPro

SimaPro is a widely used life cycle assessment (LCA) software developed by PRé Sustainability. It provides a comprehensive platform for conducting environmental assessments of products, materials, and processes using life cycle thinking principles. SimaPro enables users to model complex life cycle inventories, assess environmental impacts across multiple impact categories (e.g., carbon footprint, water consumption, resource depletion), and generate detailed reports and visualizations to communicate results to stakeholders. With its extensive database of life cycle inventory data and flexible modeling capabilities, SimaPro supports informed decision-making and sustainable design practices in the building industry.

8.1.4.2 GaBi

GaBi, developed by thinkstep AG, is another leading life cycle assessment (LCA) software solution for assessing the environmental performance of products, processes, and systems. GaBi offers a comprehensive database of life cycle inventory data and impact assessment methods, allowing users to model and analyze the environmental impacts of building materials, construction processes, and building operations. GaBi's user-friendly interface, robust modeling capabilities, and advanced reporting features make it a valuable tool for conducting life cycle assessments, optimizing environmental

performance, and supporting sustainable building design and decision-making.
Together, SimaPro and GaBi provide powerful tools for quantifying and managing the environmental impacts of buildings throughout their lifecycle, helping stakeholders identify opportunities for improvement, minimize environmental footprints, and advance sustainability goals in the built environment [346]

8.2 Appendix II: A Step-by-Step Guide to Using Meteonorm, Climate Consultant, SketchUp, and TRNSYS for Building Energy Simulation

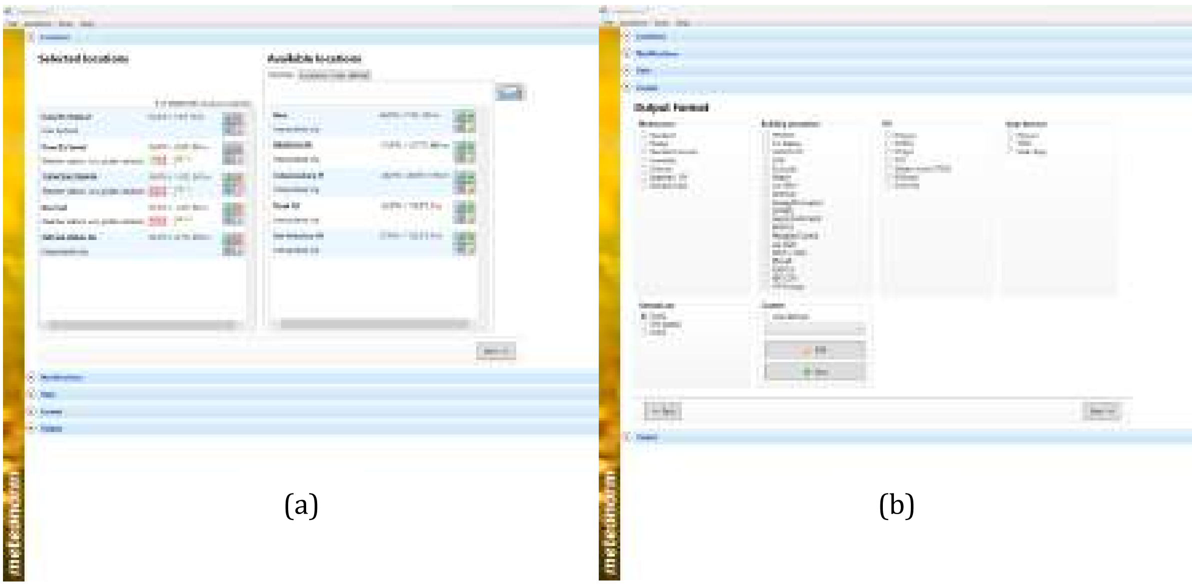
This section provides essential guidelines for utilizing software tools to assess building energy performance. It covers various aspects, starting from extracting and accessing meteorological data and visualizing climate patterns using Meteonorm and Climate Consultant. It then delves into the necessary steps to create detailed 3D models using SketchUp and provides the essential inputs required to conduct energy simulations with TRNSYS. This comprehensive guide offers a step-by-step approach, ensuring users have the necessary knowledge and techniques to effectively leverage these software tools for building energy analysis.

8.2.1 Meteonorm

Meteonorm is a widely used software tool in the fields of architecture, engineering, and renewable energy. It provides meteorological data and calculations related to solar radiation, temperature, humidity, wind speed, and other climate parameters. This data is crucial for various applications, including building energy simulations, solar energy system design, and environmental impact assessments. Meteonorm allows users to access accurate and reliable climate data from meteorological stations worldwide, facilitating realistic simulations and analyses for a wide range of projects [307].

Meteonorm works by aggregating and processing meteorological data from various sources worldwide. It utilizes algorithms and models to generate accurate climate data sets, including solar radiation, temperature, humidity, wind speed, and other relevant parameters. Users can input specific geographical locations or coordinates to retrieve relevant climate data for their projects. The software then provides this data in a user-friendly format, allowing for easy integration into building energy simulations, solar energy system design, and other applications. Meteonorm's comprehensive database and advanced algorithms ensure reliable and realistic results, making it a valuable tool for professionals in the fields of architecture, engineering, and renewable energy. In addition, the ambient temperature is interpolated using data from six weather stations at Beni-Saf (9 km), Oran (68 km), Tlemcen (42 km), Melilla (152 km), Taoumia (150 km), Oujda (88 km) [307].

As we engage with Meteonorm V7.1 [307] to extract and save data as TMY2 and EPW files, the process unfolds systematically within the software's interface. Figure 8-1(a) showcases the intuitive interface of Meteonorm, where inputting specific latitude and longitude coordinates or selecting predefined locations from the software's database is facilitated. Once the location is established, defining the desired time period for the data, whether for a single year or a range of years, follows suit. With these parameters set, configuring the output to include relevant climate variables such as solar radiation, temperature, humidity, wind speed, and precipitation becomes the next step. Figure 8-1(b) illustrates the output format selection, with options including TMY2 for TRNSYS and EPW for Climate Consultant. Navigating through the software's interface, and initiating the generation of the TMY2 or EPW file is crucial, ensuring the appropriate file format is selected during the export process. Throughout this process, attentiveness to on-screen instructions and prompts is crucial for accurate and successful data extraction. Upon completion, the resulting TMY2 or EPW file contains comprehensive climate data for the specified location and time frame, ready to be integrated into further building energy simulations or analyses.



(a) (b)

Figure 8-1 Meteonorm software (a): Interface and (b): Output Format

The solar radiation profile of El Hillal, Ain Temouchent, Algeria, was analyzed using data obtained from Meteonorm software, ranging from 82 kWh/m^2 to 242 kWh/m^2 annually. Figure 8-2(a) illustrates the monthly distribution of solar radiation over one year, indicating higher levels from March to October and lower levels from November to

February, with December marking the minimum. This variability is crucial for ensuring continuous power supply. The analysis, vital for designing and integrating energy systems, shows consistently high total solar radiation levels from March to October, with an annual total of 1898 kWh/m^2/year. Peaks occur from March to September, and the lowest levels are in December and January. This study utilizes data from the lowest radiation month to ensure optimal design.

Figure 8-2(b) revealed notable variations in global radiation. Peak global radiation, recorded at 8.6 kWh/m^2 in July, emphasizes the need for cooling in El Hillal for over four months annually. Solar radiation shows potential for solar thermal cooling systems in residential and commercial buildings. Analysis of daily variation in global solar radiation across different periods reveals distinct patterns. Regions 1 and 3, spanning January to March and November to December, exhibit multiple minima due to cloudy skies, while region 2, from April to October, shows a smoother curve, indicating less cloud cover. Annual minimum and maximum global radiation values are recorded at 0.53 kWh/m^2 in January and 8.6 kWh/m^2 in July, respectively, highlighting the influence of seasonal changes on solar radiation patterns.

The range of monthly temperatures fluctuates throughout the year, as depicted in Figure 8-2(c). The graph illustrates the variations in temperature from month to month, with January and July showing the most significant differences. During January, the temperatures range from a minimum to a maximum, while July experiences the widest fluctuations, with mean monthly temperatures of 14°C and 27.6°C, respectively.

Figure 8-2(d) presents the daily temperature distribution, indicating both the minimum and maximum values of the monthly temperature distribution. The annual highest temperature, recorded in July, peaks at 35.9°C, while the lowest temperature, observed in January, drops to 6.9°C.

The interpretation of Figure 8-2(e) illustrates the seasonal variations in both average temperature and rainfall. This region, characterize by hot summers and temperate, rainfall peaks between October and March, with a maximum of 63 mm recorded in November. Conversely, precipitation levels drop significantly from April to September, with July experiencing the lowest mean total monthly precipitation at just 1 mm. Overall, the average total annual precipitation stands at 323 mm.

Figure 8-2(f) displays the average monthly hours of sunshine. The data reveals an average daily duration of sunshine estimated at 7.1 hours per day. This information proves invaluable for studying natural lighting patterns and assessing the potential for solar energy utilization. Additionally, it facilitates the calculation of electrical energy generation through photovoltaic panels and aids in determining the load requirements for domestic hot water systems (SDHW) using solar panels.

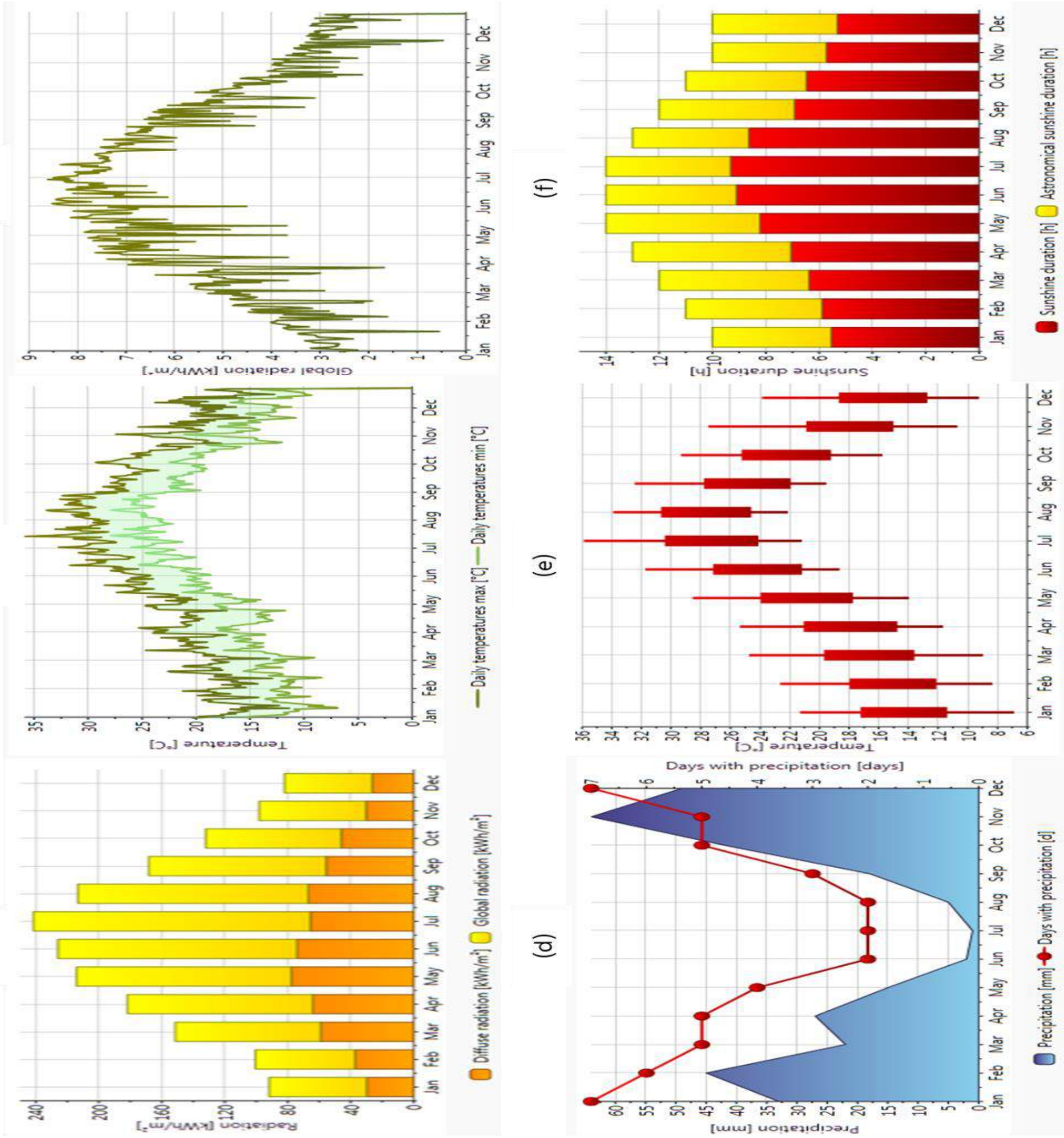


Figure 8-2 Weather data for El Hillal, Ain Temouchent, Algeria; (a): Monthly distribution of solar radiation; (b): Daily Variation of Global Solar Radiation; (c): Monthly Temperature Range;(d): Daily temperature distribution;(e): Seasonal average temperature and seasonal rainfall; (f): Average Hours of sunshine

8.2.2 Climate Consultant

Climate Consultant is a versatile software tool widely utilized in architecture and engineering disciplines. It empowers users to visualize and analyze climate data, aiding in the assessment of building energy performance and environmental comfort. By facilitating the evaluation of various climatic parameters such as solar radiation, temperature, humidity, and wind speed, Climate Consultant informs decisions regarding building design, energy efficiency strategies, and sustainability practices [309].

The software operates by granting users access to an extensive array of climatic data and visualization tools. Users can input specific geographic locations or choose from a database of predefined sites to acquire pertinent climate information. Subsequently, Climate Consultant generates visual representations of climate conditions, including charts, graphs, and diagrams, enabling effective data interpretation and analysis. Moreover, the software offers functionality for evaluating the potential impact of climate factors on building performance, such as solar radiation patterns, temperature fluctuations, and wind velocities. Overall, Climate Consultant serves as an invaluable resource for architects, engineers, and researchers striving to comprehend and address the influence of climate on building design, energy efficiency, and environmental sustainability [309].

To extract data from the EPW file obtained from Meteonorm using Climate Consultant, begin by launching the Climate Consultant software. Import the EPW file corresponding to the studied region and select the type of building, whether residential or non-residential. Define the comfort parameters based on the building type and occupants' requirements. The Climate Consultant will then display a comprehensive set of climatic parameters, including solar radiation, temperature, humidity, and wind speed, specific to the selected location and time period. Utilize the software's tools and features to visualize and analyze the climate data as needed. Additionally, explore options within Climate Consultant to export the analyzed data or generate reports for further use in building energy simulation or environmental analysis.

The data presented here represents a selection of extracted information from the EPW file, skillfully visualized and plotted using Climate Consultant. Through this software, key parameters such as temperature, solar radiation, humidity, and wind speed have been analyzed and presented graphically, offering valuable insights into the climatic conditions of the studied region. This visualization serves as a crucial tool for understanding and assessing the environmental context and potential implications for building design, energy efficiency strategies, and sustainability practices.

This chart depicts the monthly average temperature variations in El Hillal, Ain Temouchent, Algeria as illustrated in Figure 8-3. High and low temperatures for each month are denoted by round dots, with January recording the lowest and July the highest temperatures. The upper and lower bounds of the green bars represent the extreme temperatures, while the top and bottom of the yellow bars indicate the average high and low temperatures, respectively. The mean or average temperature is represented by an open slot. These values are calculated for each month. The light grey color signifies the summer temperature range, while the dark grey color indicates the winter temperature range, both conforming to the adaptive range of thermal comfort as per the ASHRAE Standard-55.

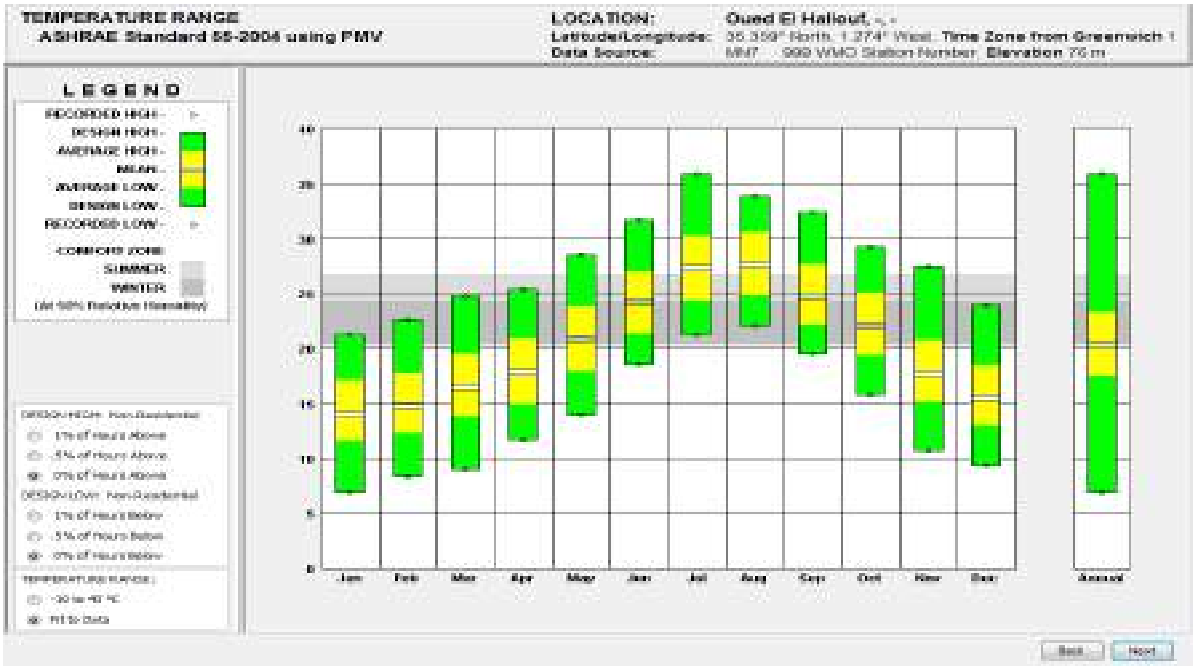


Figure 8-3 Evolution of monthly average temperature in El Hillal, Ain Temouchent, Algeria

This diagram provides a comprehensive view of the diurnal (24 hours) average data for each hour of every month throughout the year, as depicted in Figure 8-4. It presents the average dry bulb temperature (upper red curve) and average wet bulb temperature (lower red curve) against a grey bar denoting the comfort range specified by ASHRAE Standard 55, all in degrees Celsius. The light blue area beneath the dry bulb temperature curves illustrates the temperature for each hour of the day over the year. Notably, the small difference between the dry-bulb and wet-bulb temperatures indicates moisture in the air, characterizing this area. Additionally, the average hourly radiation for each month is depicted on the left-hand scale in (Wh/m^2), with global horizontal radiation shown in green, direct normal radiation in yellow, and diffuse radiation in blue. Higher diffuse radiation suggests overcast skies, potentially reducing direct normal beam radiation and total or global horizontal radiation. This observation aligns with months from November to February, indicating more overcast skies during this period.

- ❖ *Global Horizontal:* is the solar radiation in the entire region. In theory, it is composed of all the diffuse radiation from the total sky vault plus the direct radiation from the sun-times the cosine of the angle of incidence. This is sometimes also called total horizontal radiation.
- ❖ *Direct Normal:* is the radiation coming directly from the sun. This is sometimes called beam radiation.
- ❖ *Diffuse Radiation:* is the radiation reflected from the surfaces in the area.

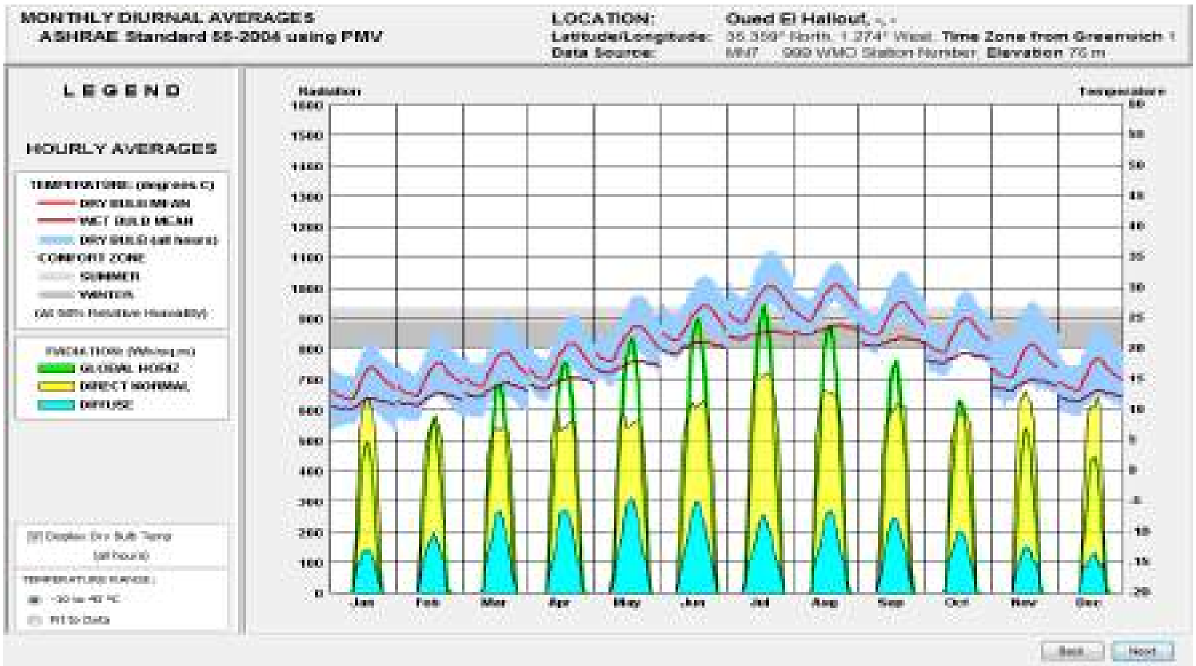


Figure 8-4 Diurnal averages of monthly temperatures and monthly solar radiation levels in El Hillal, Ain Temouchent, Algeria

Figure 8-5 provides an insightful depiction of the hourly averages of radiation range. This visualization serves as a valuable tool for energetically analyzing radiation, particularly for solar panel utilization. The graph illustrates angles of tilted surface radiation, crucial for optimizing solar panel orientation. The first angle, as depicted in Figure 8-6(a), indicates the rotation of the panel from horizontal to vertical, aligning it directly with the sun (south). The second angle, showcased in Figure 8-6(b), pertains to the panel's rotation towards east and west, facilitating sun-tracking capabilities. The colors on the graph denote different types of radiation: yellow represents direct normal radiation reaching the panel, green signifies solar radiation reaching the horizontal surface (Global horizontal), and orange indicates radiation reaching all surfaces irrespective of angle.

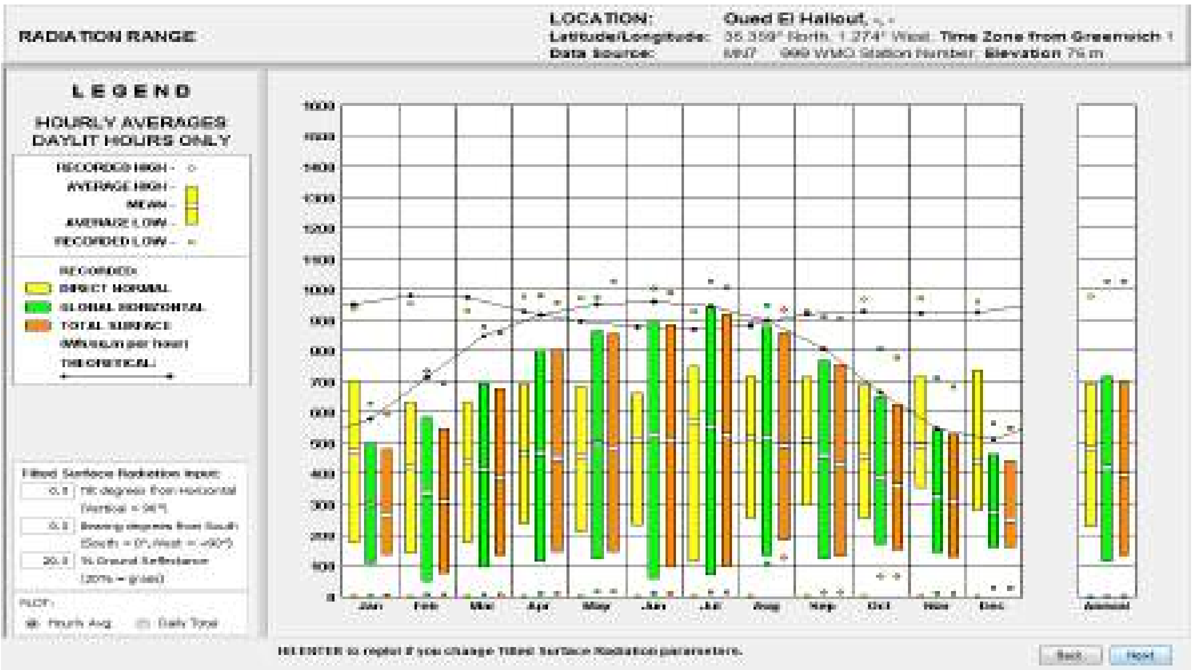


Figure 8-5 Hourly averages of radiation range in El Hillal, Ain Temouchent, Algeria

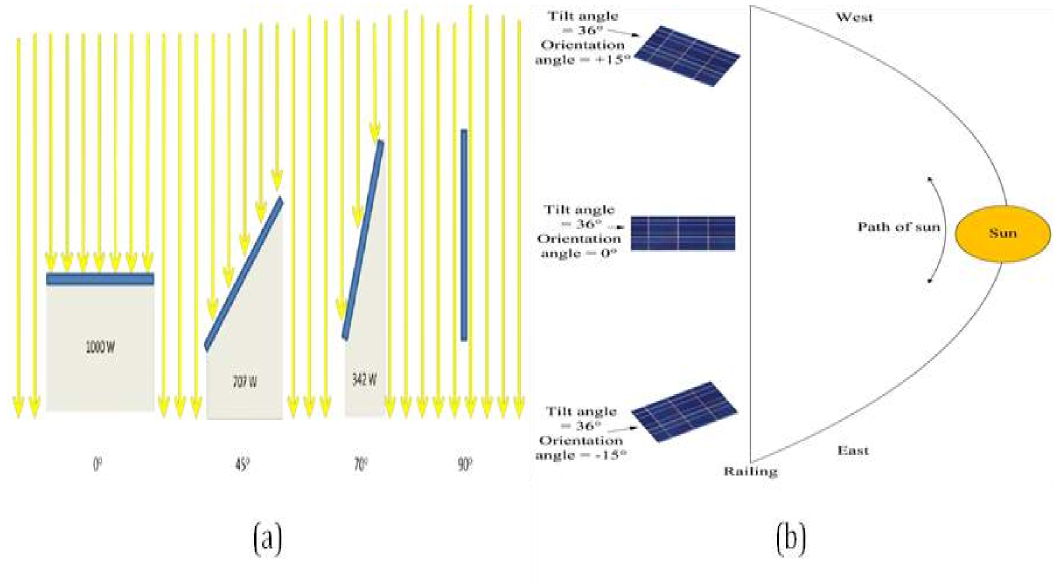


Figure 8-6 Solar radiation analysis; (a): Titled angle [347] and (b): Orientation angle [348]

The Visible Direct Normal Illumination shows for each month the Recorded High and Low

Daily value (green dot), the Average High and Low value (top and bottom of the yellow bar), and the Daily Mean Illumination (center of the yellow bar). These same variables are shown in green bars for Global Horizontal Illumination. The unit is in Lux (also called lumens per square meter) [309].

- *Direct Normal Illumination:* Direct Normal Illumination is defined as the visible light from the sun that is measured by a narrow-angle meter pointed directly at the sun and that excludes the surrounding sky. The unit is in Lux (also called lumens per square meter) [309].
- *Global Horizontal Illumination:* Global Horizontal Illumination is defined as the total visible light that falls on a horizontal surface from the entire sky vault plus Direct Normal Illumination from the sun. The unit is in Lux (also called lumens per square meter) [309].

Figure 8-7 presents an illumination chart, measured in lux, providing valuable insights into natural lighting conditions. Analysis reveals significant illumination levels, particularly from March to October, with peak intensity occurring during the summer months, notably in July, where levels may reach up to 110,000 lux. This abundance of natural light in the area underscores its potential for strategic utilization in design considerations.

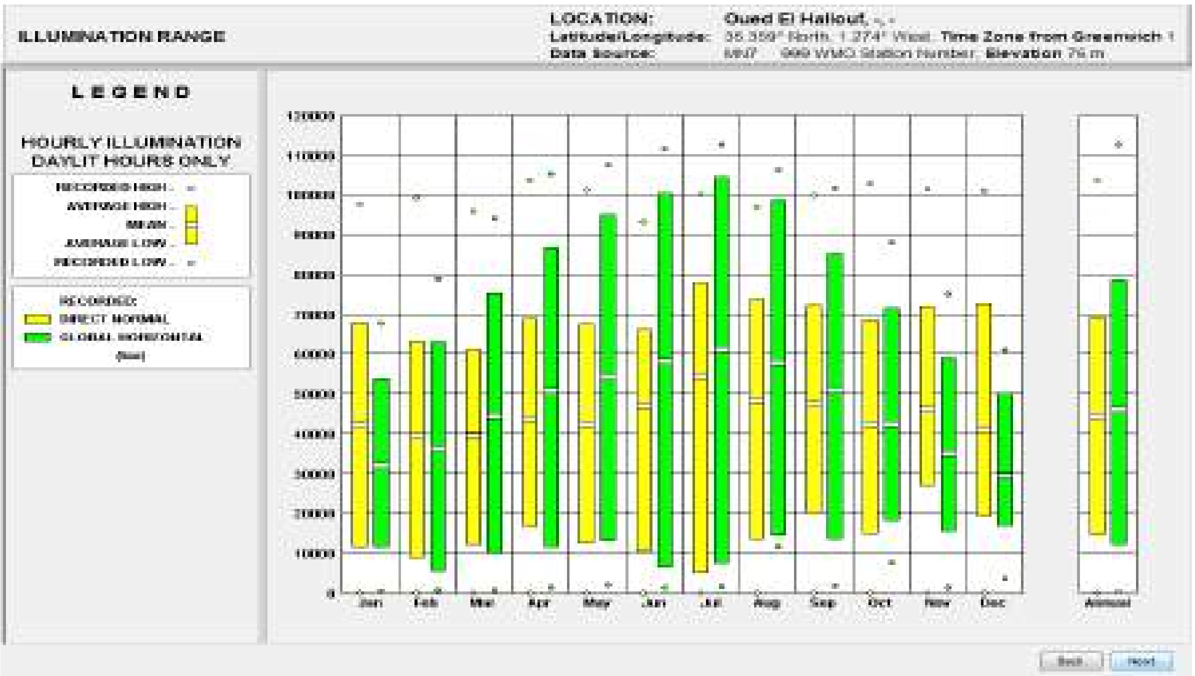


Figure 8-7 Illumination range in El Hillal, Ain Temouchent, Algeria

Figure 8-8 provides a comprehensive overview of sky cover for each month and the entire year. Sky cover is represented as a percentage, with clear skies indicated by 0% and complete cloud cover by 100%. This data is crucial for understanding solar cell performance and efficiency. Notably, the highest sky cover percentage was recorded in February, reaching 76%, while the annual average stands at 36%. Despite fluctuations, this area demonstrates favorable conditions for solar cell efficiency compared to other regions.

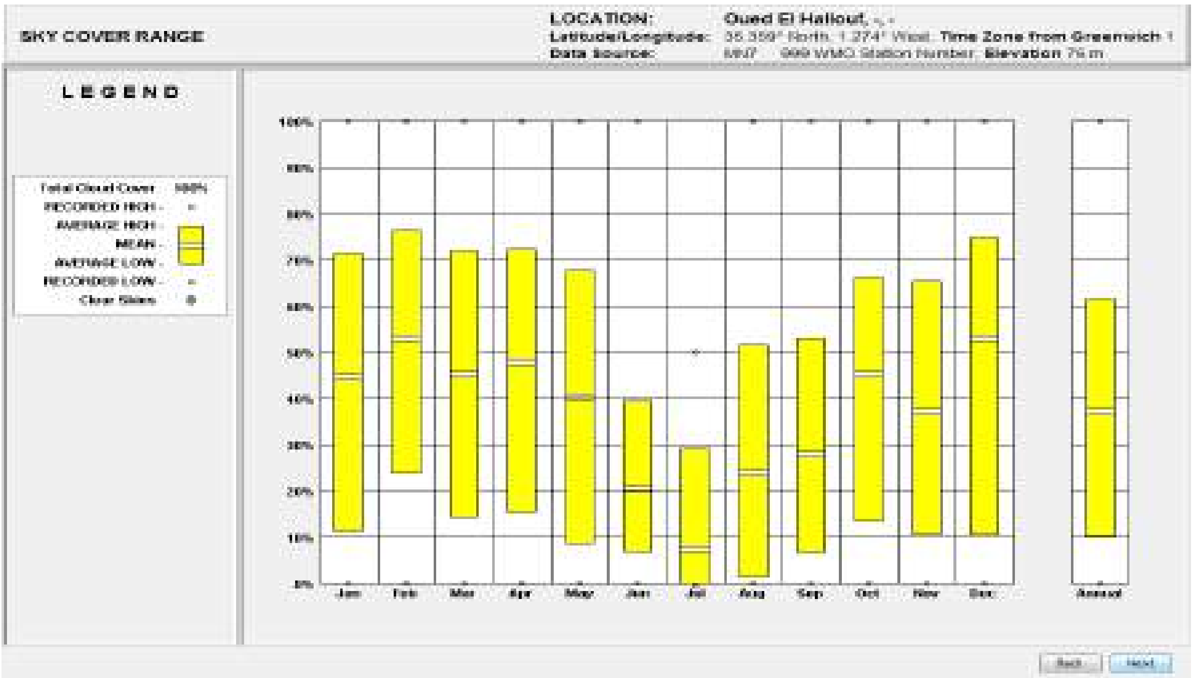


Figure 8-8 Distribution of monthly sky cover on El Hillal, Ain Temouchent, Algeria

Figure 8-9 provides detailed insights into wind velocity, measured in meters per second (m/s), for each month and the entire year. The chart displays recorded high and low values, as well as average high and low velocities. Wind speed is crucial for various applications, including wind energy production and natural ventilation. While the annual wind speed in this area does not exceed 6 m/s, it's essential to note that energy production through wind turbines is typically optimal when wind speeds range between 15 m/s to 25 m/s, as depicted in Figure 8-10. Despite this, understanding local wind patterns is valuable for maximizing natural ventilation and exploring potential energy opportunities.

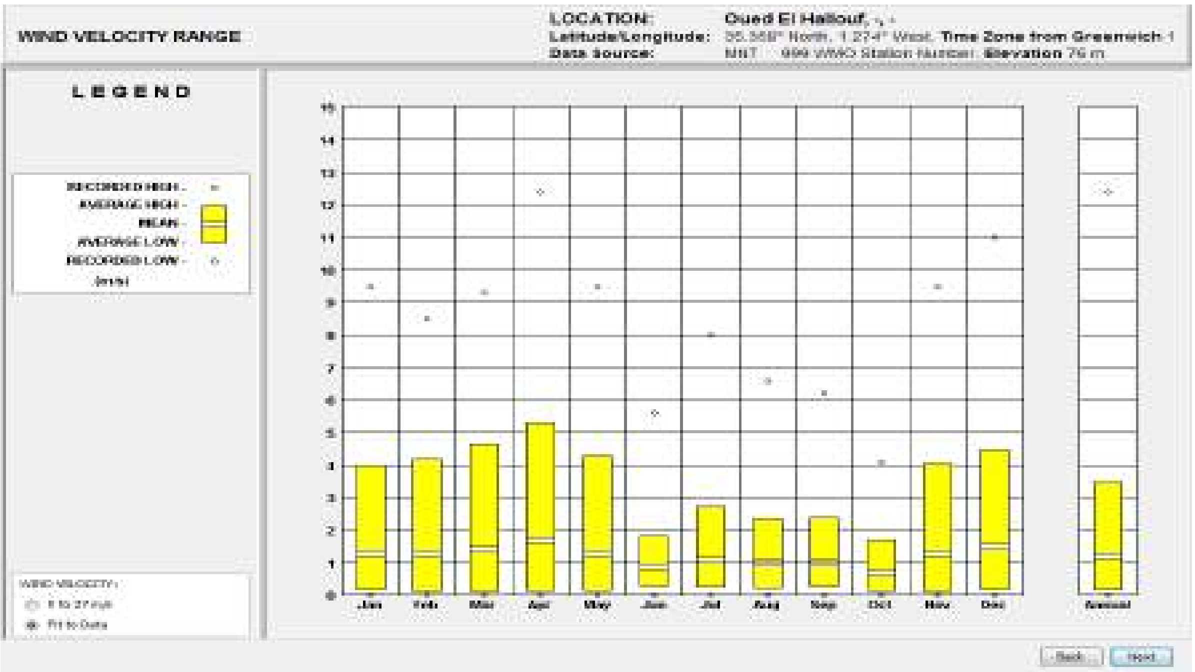


Figure 8-9 Monthly wind velocity in El Hillal, Ain Temouchent, Algeria

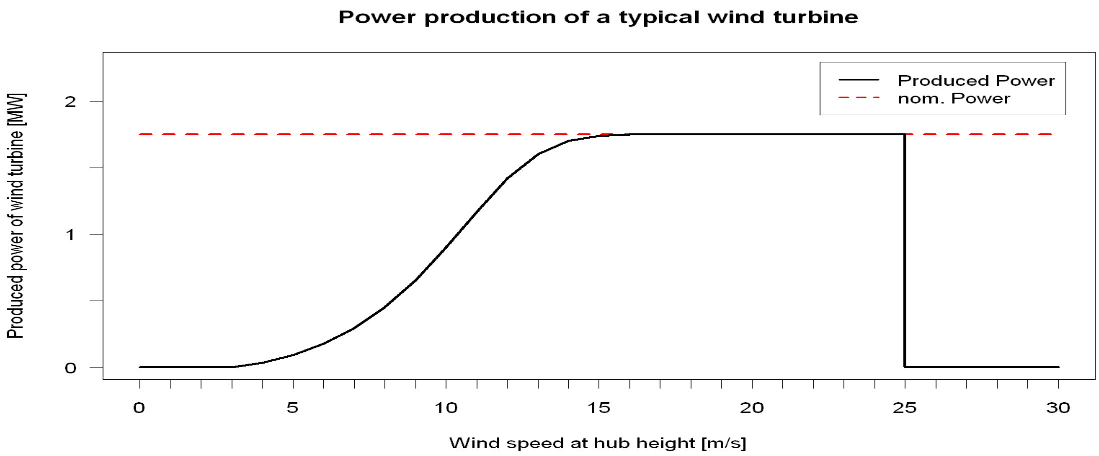


Figure 8-10 Power production of typical wind turbine [349]

Figure 8-11 illustrates the monthly average ground temperature at a depth of 1 meter, providing essential insights into soil temperature dynamics throughout the year. In winter, the temperature remains relatively stable around 19°C, gradually decreasing during the colder months. Conversely, summer months witness higher temperatures, with September recording the highest at 24°C. This chart highlights a temperature difference of 5°C between summer and winter, a variation that diminishes with increased depth into the ground. Understanding ground temperature fluctuations is crucial for leveraging geothermal heat for both cooling and heating purposes, demonstrating the potential for sustainable energy utilization.

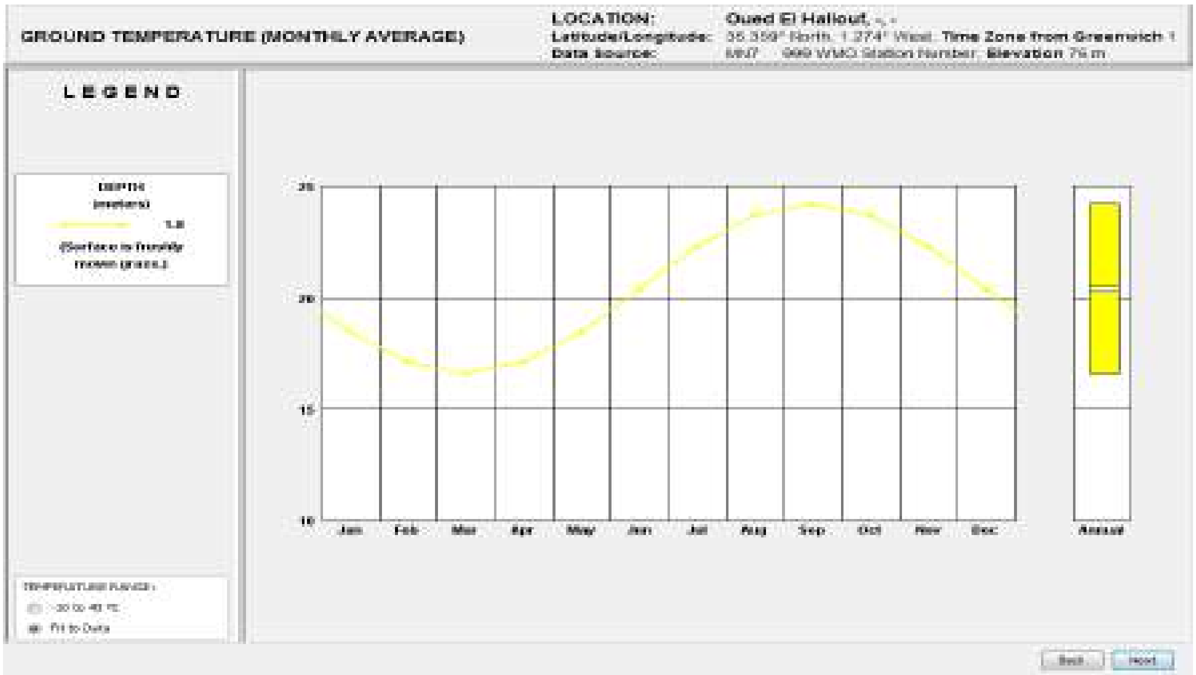


Figure 8-11 Monthly average ground temperature

The wind wheel, as depicted in Figure 8-12, provides a comprehensive overview of wind characteristics, including direction, frequency, and velocity, throughout the year. In this visualization, each wind direction is represented along with its corresponding wind velocity and frequency of occurrence. The outer ring illustrates the percentage of hours with winds from each direction, while subsequent rings display average temperature and humidity associated with those wind directions. Blue shades indicate cooler temperatures, with light blue representing temperatures between 0-21 °C and dark blue indicating temperatures between 21-27 °C. Similarly, green shades represent humidity levels, with light green indicating comfortable levels (30-70%) and dark green indicating higher humidity (>70%). Wind velocity is represented by triangles, with light orange depicting low speeds and dark orange depicting high speeds. This visualization aids in understanding wind patterns and their potential for natural ventilation, essential information for architectural design and environmental comfort considerations.

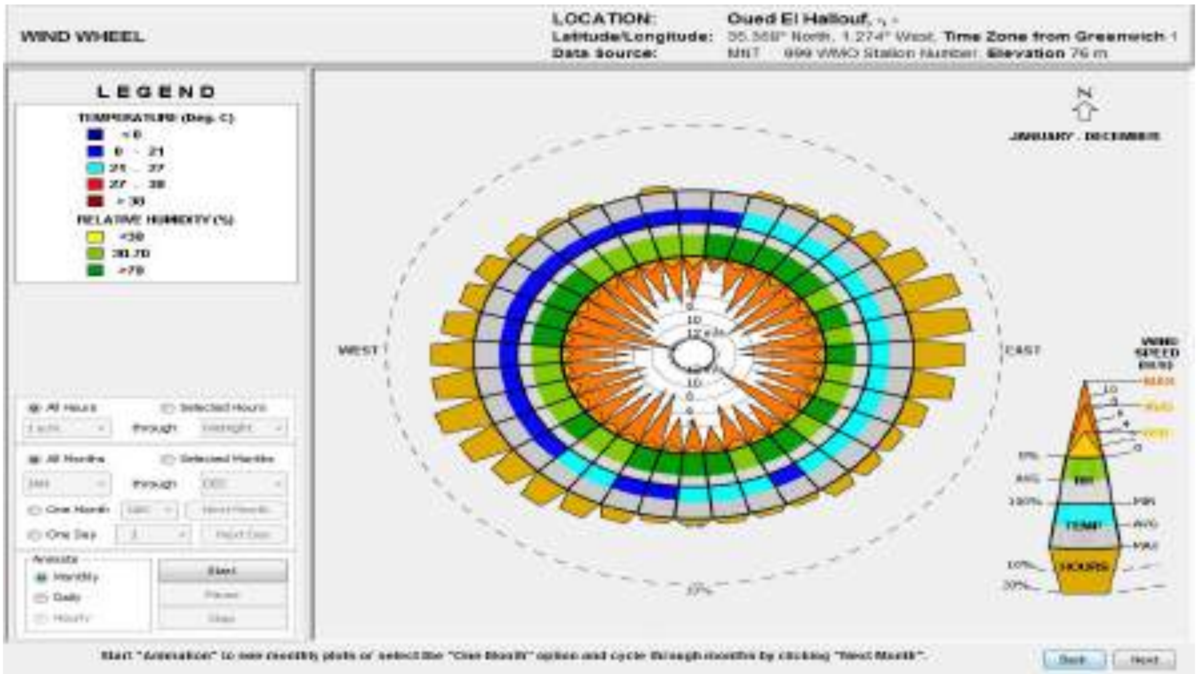


Figure 8-12 Wind wheel

In our study utilizing Climate Consultant, the primary focus will be on extracting key results from the EPW file, specifically the Sun Shading Chart, Psychrometric Chart, and Design Strategies. These extracted data sets are crucial for analyzing and understanding the climatic conditions of the studied location. The Sun Shading Chart provides insights into solar radiation patterns and shading requirements, aiding in passive heating and cooling strategies. The Psychrometric Chart offers comprehensive information on air properties, including temperature, humidity, and enthalpy, essential for assessing indoor comfort conditions and HVAC system design. Additionally, Design Strategies derived from the EPW file analysis guide the development of efficient building design and energy management approaches tailored to the specific climatic context. By focusing on these key results, our study aims to inform sustainable design practices and enhance the overall performance and comfort of built environments.

8.2.2.1 Sun Shading Chart

The Sun Shading Chart provides a comprehensive view of the sun's bearing and altitude throughout the year, depicted by colored dots. Yellow dots signify comfort conditions, indicating that the dry bulb temperature falls within the defined comfort zone. Conversely, red dots denote overheat conditions, occurring when the temperature exceeds the upper limit of the comfort range. Blue dots represent underheat conditions, occurring when temperatures are below the lower limit of the comfort zone. This chart serves as a valuable tool for passive heating strategies, suggesting full exposure for windows during blue dot periods to maximize solar gain and recommending full shading during red or yellow dot periods to prevent overheating.

The sun shading chart offers users the flexibility to customize shading options according to their specific needs. Two key options are available in the chart legend: the shading calculator for defining shading masks or fins and overhangs, and the obstruction elevation overlay for shading overlays on remote objects. Depending on the selected overlays, the legend provides information on the number of unshaded hours during different seasons: during the cool season when solar gain is desirable, the hot season when shading is necessary, and comfort hours when solar gain is not required. For instance, if neither overlay is displayed, all hours are assumed shaded; displaying just the shading calculator shades only those hours masked by fins and overhangs, while displaying just the obstruction elevation overlay shades hours covered by vertical bars representing shading objects. If both options are displayed, hours shaded by either or both are counted, ensuring accuracy without double-counting hours [309].

- ❖ *Plot Months:* There can be two different sets of Plot Months, one for winter and spring (December 21 to June 21), and the other for summer and fall (June 21 to December 21). Switching between these two will show that summer and fall have many more overheat hours.

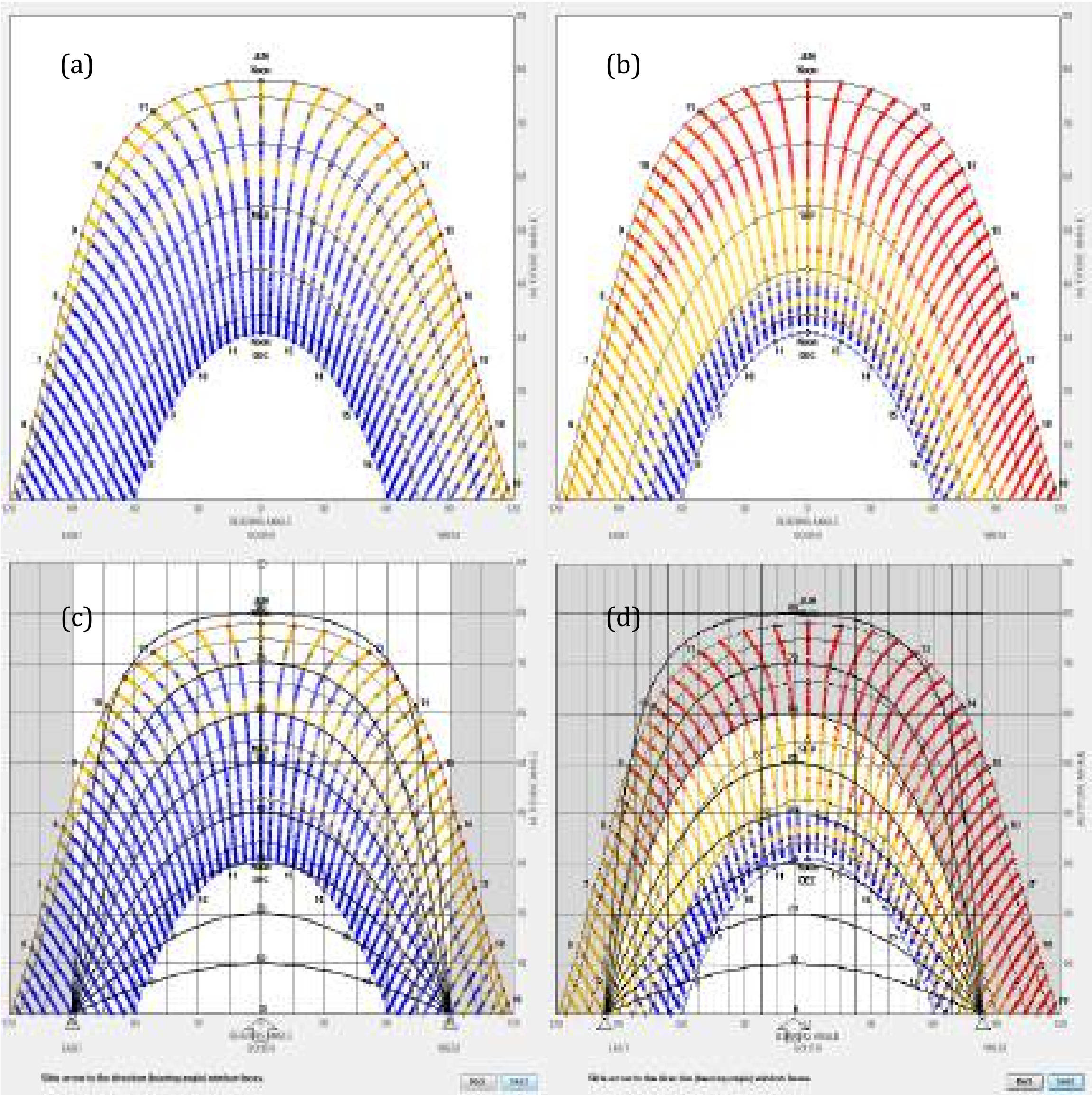


Figure 8-13 Sun shading chart;(a): Sun shading chart (Winter-Spring), (b): Sun shading chart (Summer-Fall), (c): Calculate the angle of shading (Horizontal and vertical shading), for Winter-Spring, (d): Calculate the angle of shading (Horizontal and vertical shading)

Two distinct Sun Shading Charts for Winter-Spring and Summer-Fall, each presenting crucial insights into temperature variations and shading requirements throughout the year, are illustrated in Figure 8-13. Yellow, red, and blue dots denote comfort, overheat, and underheat conditions, respectively, based on ASHRAE Standard 55 criteria. During Winter-Spring, from December 21st to June 21st, shading isn't preferable to maximize solar gains. Conversely, shading is vital in Summer-Fall, from June 21st to December 21st, to mitigate overheating. Horizontal shading, crucial during these periods, is optimized at a vertical shading angle (VSA) of 60°, as illustrated in Figure 8-13(d). Vertical breakers have minimal impact on cooling loads. Utilizing horizontal shading predominantly on the southern side aligns with the sun's angle, aiding in passive heating during winter and shading during summer. Figures 3-2 and 3-3 further elucidate shading calculations and optimal device orientations, enhancing design efficiency. [251,252].

8.2.2.2 Psychrometric chart

The psychrometric chart serves as a vital tool for analyzing air temperature and humidity relationships, essential for understanding climate data and human thermal comfort conditions. Positioned with dry bulb temperature along the bottom and moisture content of the air on the side, this chart depicts the absolute humidity or humidity ratio, providing insights into the air's vapor pressure. The saturation line, curving on the left, signifies 100% relative humidity and illustrates the inverse relationship between air temperature and its moisture-holding capacity. Each dot on the chart represents an hour in the EPW climate data file, where multiple dots may denote recurring temperature and humidity conditions. Furthermore, dots may fall within multiple strategy zones, contributing to percentages that surpass 100%. The coloration of each dot, typically green for comfort and red for discomfort, is determined by predefined comfort criteria as depicted in Figure 8-14. This comprehensive visualization facilitates the assessment of thermal comfort and aids in the formulation of effective design strategies for built environments.

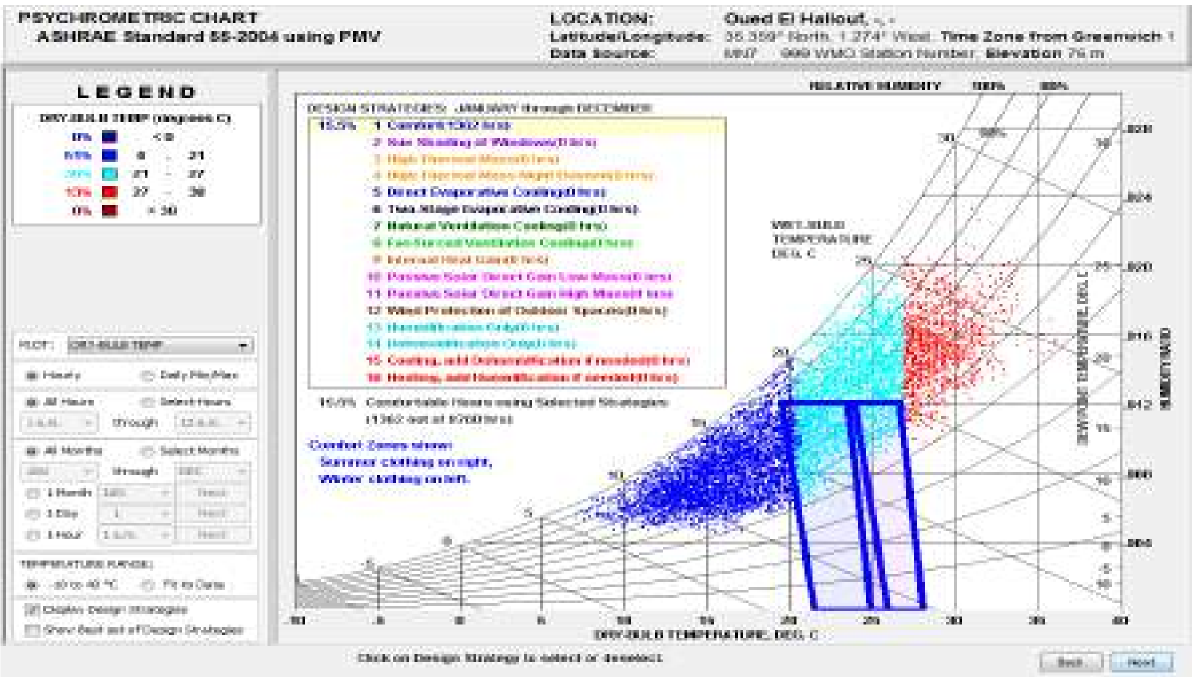


Figure 8-14 Psychrometric chart of dry bulb temperature, during all the year

8.2.2.3 Design Strategies

Design strategies play a pivotal role in shaping the built environment, particularly in climates where envelope characteristics significantly impact thermal comfort. This holds true for structures like residences, educational institutions, and small commercial establishments, where the building envelope's design profoundly influences indoor conditions. Unlike larger facilities where internal factors like equipment and occupant loads predominate, these buildings' thermal performance relies heavily on external factors. The design strategies outlined, typically depicted relative to the comfort zone, provide actionable guidelines for optimizing indoor conditions. These strategies are tailored to specific climatic conditions, ensuring that building envelopes effectively mitigate external influences while maintaining occupants' comfort. The criteria defining each strategy zone, essential for their implementation, are detailed on the criteria screen, offering a comprehensive framework for informed decision-making in building design.

- *Comfort Zone:* The Comfort Zone, delineated on the Criteria screen, establishes optimal indoor conditions, primarily based on Dry Bulb Temperature. It's prominently depicted on the Psychrometric Chart and may also consider factors like Humidity and seasonal clothing.
- *Sun Shading Zone:* Defined on the Criteria screen and visible on the Psychrometric Chart, the Sun Shading Zone typically starts at or below the Comfort Low. It's characterized by specific outdoor temperature thresholds and minimum total horizontal radiation levels. Sun shading techniques are instrumental in outdoor spaces and window treatments to regulate radiant temperatures and prevent indoor temperatures from surpassing ambient levels. However, hours assumed to be shaded are not included in the total comfortable hours count, as shading alone doesn't ensure comfort.
- *High Thermal Mass Zone:* In hot, dry climates, employing high thermal mass interiors during summer serves as an effective cooling strategy. This approach capitalizes on thermal storage, time lag, and damping effects, resulting in reduced daily indoor temperature fluctuations despite high outdoor temperature swings. The building remains closed during the day, coasting through elevated temperatures. Additionally, in winter, high mass construction offers some warming benefits when outdoor temperatures reach the comfort zone,

particularly if complemented by Passive Solar Direct Gain.

- *High Thermal Mass with Night Flushing Zone:* In hot, dry climates, utilizing high thermal mass interiors, along with natural ventilation or a whole-house fan, is a strategic cooling approach. By harnessing the thermal storage and time lag effects of the mass, the building can effectively endure high daytime temperatures by capitalizing on cool night air influxes. This method mitigates indoor temperature fluctuations, translating high outdoor temperature swings into minimal indoor variations.
- Displayed on the Psychrometric Chart below and to the right of the Comfort Zone, the Direct Evaporative Cooling Zone utilizes evaporative cooling, where water transitions from liquid to gas, absorbing latent heat and lowering air temperature while increasing humidity. This method, following the Wet Bulb Temperature line on the chart, proves effective in hot, dry climates, automatically defined by the highest and lowest Wet Bulb Temperatures falling within the comfort zone.
- *Two-Stage Evaporative Cooling Zone:* A variant of the Direct Evaporative Cooling Zone, the Two-Stage Evaporative Cooling Zone is delineated on the Psychrometric Chart and involves a modified approach. It resembles the Direct Evaporative Cooler but features an increased angle in the upper boundary relative to the efficiency of the Indirect Phase. In the first stage, evaporation cools the exterior of a heat exchanger, with incoming air drawn into the second stage for direct evaporation cooling.
- *Natural Ventilation Cooling Zone:* Located above and to the right of the Comfort Zone on the Psychrometric Chart, the Natural Ventilation Cooling Zone is defined on the Criteria screen. In hot, humid climates, where airflow is crucial for human comfort, natural ventilation plays a significant role. By promoting sweat evaporation and providing a psychological perception of cooling, airflow enhances comfort, although it does not directly lower the dry-bulb temperature. Wind velocities are influenced by surrounding objects.
- *Fan Forced Ventilation Cooling Zone:* Positioned above and to the right of the Comfort Zone on the Psychrometric Chart, the Fan Forced Ventilation Cooling Zone is delineated on the Criteria screen. In hot, humid climates, where airflow is vital for comfort, this zone signifies the use of fan-forced air motion, facilitated by

centralized mechanical fans, ceiling fans, or localized desk or table fans. While ventilation does not directly reduce the dry-bulb temperature, it enhances comfort by promoting sweat evaporation and creating a perception of cooling.

- *Internal Heat Gain Zone:* Positioned to the left of the comfort zone on the Psychrometric Chart, the Internal Heat Gain Zone is defined on the Criteria screen. It provides an approximation of the heat contributed to a building by internal sources such as lighting, occupants, and equipment, influenced by the building's type and design. The Balance Point Temperature within this zone indicates the outdoor temperature at which internal heat alone maintains indoor comfort.
- *Passive Solar Direct Gain High/Low Mass Zone:* Displayed to the left of the Comfort Zone on the Psychrometric Chart, the Passive Solar Direct Gain High/Low Mass Zone is delineated on the Criteria screen. Represented by a dashed line due to its reliance on building design, this zone indicates the potential for passive solar heating to elevate indoor temperatures when buildings feature adequate sun-facing glass.
- *Wind Protection of Outdoor Spaces:* Depicted as vertical lines either above or below the comfort zone on the Psychrometric Chart, the Wind Protection of Outdoor Spaces zones are defined on the Criteria screen. These zones signal periods when outdoor spaces are uncomfortable due to cold or hot winds, necessitating windbreaks for protection. Hours meeting specified criteria for wind velocity and temperature are included. While these zones impact outdoor comfort, they do not directly influence indoor comfort and are thus not included in total indoor comfort hours.
- *Humidification Zone:* Defined on the Criteria screen and situated directly below the bottom of the Comfort Zone on the Psychrometric Chart, the Humidification Zone indicates indoor air within the dry bulb comfort range but lacking sufficient moisture. While modern buildings often acquire moisture through human activities, typical humidifiers can adjust Absolute Humidity, decreasing Dry Bulb temperature. This shift necessitates additional heating to maintain comfort levels within the Dry Bulb temperature range.
- *Dehumidification Zone:* Positioned on the Criteria screen and displayed above the top of the Comfort Zone on the Psychrometric Chart, the Dehumidification Zone

signifies indoor air within the dry bulb comfort range but excessively humid. Typical dehumidifiers remove moisture by passing air over cold coils, precipitating liquid water and reducing Absolute Humidity. This process requires additional heating to restore conditions to the Dry Bulb temperature range.

- *Cooling Zone (and Dehumidification if Necessary):* This zone encompasses hours when outdoor temperatures exceed the comfort range and are not classified under other cooling strategy zones. If humidity remains high, dehumidification becomes essential. This cooling process typically involves refrigerant cycle air conditioners or heat pumps. In some cases, both cooling and humidification may be necessary due to dry indoor air. However, mechanical humidification is often unnecessary due to moisture from human activities.
- *Heating Zone (add Humidification if Necessary):* Hours falling below the comfort range and not included in other heating zones belong to the Heating Zone, requiring artificial heating to achieve comfort. If air remains too dry, humidification becomes necessary. This heating process typically involves furnaces or heat pumps. While some instances may require both heating and dehumidification, specialized HVAC systems may not always be needed, as these conditions are usually limited.

8.2.2.4 Design guidelines

The Design Guidelines screen shows a list of suggestions, specific to this particular climate and a selected set of Design Strategies, to guide the design of buildings such as homes, shops, classrooms, and small offices. Architects call these envelopes dominated because they do not have large internal thermal loads and thus the design of the building's envelope will have a great deal of impact on the thermal comfort of the occupants as illustrated in Appendix III-3.

8.2.3 SketchUp

SketchUp is a widely-used 3D modeling software developed by Trimble Inc. It is renowned for its user-friendly interface and versatility, making it popular among architects, designers, engineers, and hobbyists alike. SketchUp allows users to create detailed 3D models of buildings, landscapes, interiors, furniture, and more with ease. It offers a range of tools for drawing, editing, and organizing geometry, as well as features for rendering, animation, and documentation. Whether for professional use or personal projects, SketchUp provides a powerful platform for visualizing ideas and bringing designs to life in three dimensions [338].

The TRNSYS 3D Plugin is an extension designed for SketchUp that enhances its capabilities by enabling users to create multizone buildings directly within the SketchUp environment. This plugin facilitates the drawing of complex building geometries with multiple zones, which can then be imported seamlessly into the TRNSYS Building environment, known as TRNBuild (.IDF file), for energy simulation purposes. By integrating SketchUp's intuitive 3D modeling interface with TRNSYS's powerful energy simulation capabilities, the TRNSYS 3D Plugin streamlines the process of building energy analysis and optimization, ultimately aiding in the design of more efficient and sustainable buildings [310].

Here is some information about the interface of SketchUp and TRNSYS 3D Plugin:

The interface of SketchUp and the TRNSYS 3D Plugin, as depicted in Figure 8-15, comprises several elements designed to facilitate 3D modeling and energy simulation tasks. On the left side of the screen, a vertical toolbar displays various tool icons for tasks such as selection, painting, and creating shapes. These tools enable users to create and modify 3D objects within SketchUp. At the top of the interface (first line), another toolbar provides icons for functions like saving, opening new files, and managing project files.

Moving to the right side of the screen, a dialog box titled 'Entity Info' is displayed, showing the properties of the selected entity within the model. This dialog box includes information such as entity name, layer, area, and volume. Additionally, tabs for Materials and Components allow users to apply textures and predefined objects to the 3D model.

An instructional tooltip appears to guide users on the operation of the Select Tool, which seems to be active. The tooltip provides information on how to use the tool and any modifier keys needed to select multiple or specific entities.

To utilize the TRNSYS 3D Plugin, must first install and activate the plugin from the TRNSYS website, then access it from the Extensions menu in SketchUp. The plugin adds a new toolbar containing icons for TRNSYS-related functions, such as creating zones, assigning boundary conditions, and exporting to TRNBuild as depicted on the top of the interface (second line). Additionally, a new tab labeled 'TRNSYS3D' appears on the right side of the screen, allowing users to edit TRNSYS parameters for zones and surfaces within the model.

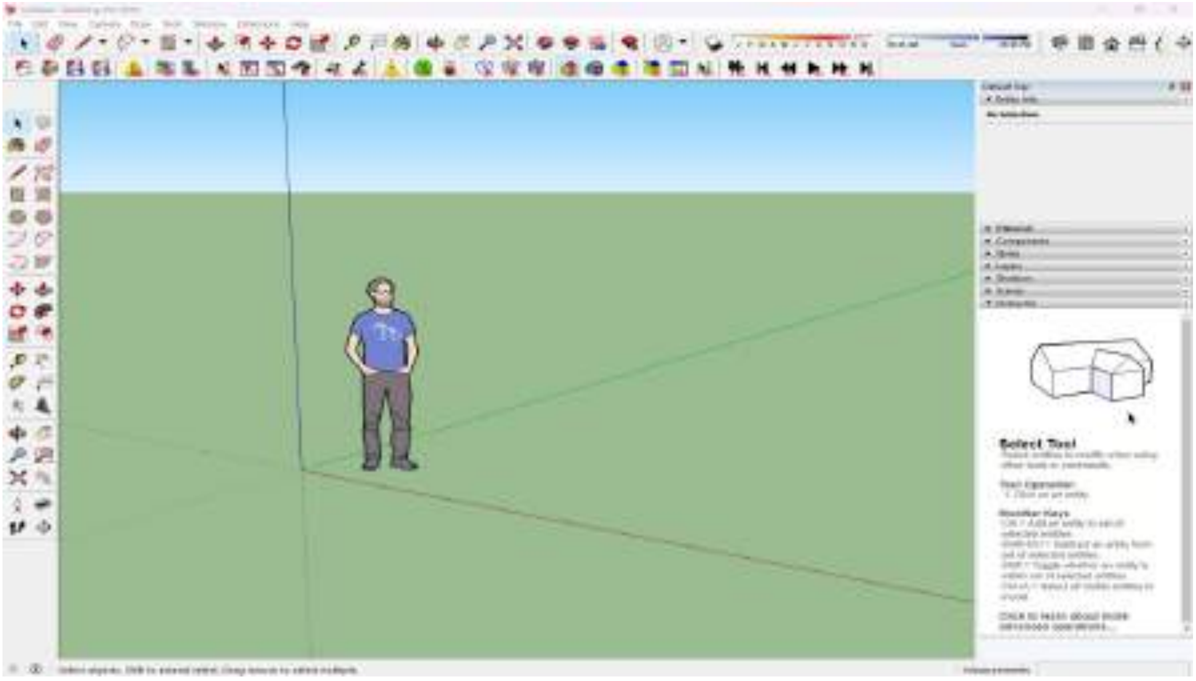


Figure 8-15 Interface of SketchUp and TRNSYS 3D Plugin

8.2.3.1 Bridging SketchUp and TRNBuild: The Role of TRNSYS 3D Plugin in Energy Simulation

8.2.3.2 Introduction to TRNSYS 3D Plugin

TRNSYS 3D Plugin serves as a bridge between SketchUp and the TRNSYS Building environment (TRNBuild), allowing us to seamlessly transition from 3D modeling to energy simulation. TRNSYS 3D enables us to create and edit zones, surfaces, windows, doors, shading devices, and boundary conditions in SketchUp and export them to TRNBuild, where the thermal performance of the building can be simulated using the TRNSYS Building Model. TRNSYS 3D is part of the TRNSYS suite of tools, which is a flexible software environment for simulating the behavior of transient systems, such as thermal and electrical energy systems, traffic flow, or biological processes [310,348].

8.2.3.3 Creating Multizone Building Models in SketchUp

A multizone building is a building that consists of several zones, each with its own thermal properties and boundary conditions. A zone can be a room, a floor, or any other part of the building that has a distinct thermal behavior.

8.2.3.4 Converting SketchUp Geometry to TRNSYS Model

To create a multizone building model in SketchUp, we can use the existing tools in SketchUp to draw the geometry of the building, such as walls, floors, roofs, windows, doors, etc. We can also apply materials and textures to the surfaces to make the model more realistic.

8.2.3.5 Defining Zones and Surfaces with TRNSYS3D Tab

To convert the SketchUp geometry into a TRNSYS model, we need to use the TRNSYS 3D Plugin to create and define zones. A zone is a group of surfaces that enclose a volume of air. We can create a zone by selecting a set of surfaces and clicking on the Create Zone icon in the TRNSYS toolbar. We can also use the pre-made zone templates that are available in the plugin. We can modify the geometry of the zone by using the SketchUp tools, such as move, rotate, scale, etc.

8.2.3.6 Exporting Models to TRNBuild

We can assign different properties and boundary conditions to the zones and surfaces using the TRNSYS3D tab. The properties include the name, layer, area, volume, orientation, etc. of the zone or surface. The boundary conditions include the type of surface (wall, floor, roof, window, door, etc.), the construction (material layers and thicknesses), the internal and external heat transfer coefficients, the solar absorptance and emittance, the shading devices, the infiltration rate, the ventilation rate, the internal gains, etc. We can also specify the movable shading for windows, predefined wall constructions, and predefined boundary temperatures using the TRNSYS3D tab.

8.2.3.7 Integration and Simulation in TRNSYS Simulation Studio

After we have created and defined all the zones and surfaces, we can export the model to TRNBuild, which is a graphical interface for the TRNSYS Building Model (Type56). TRNBuild allows us to edit and verify the building model, as well as to generate the input file for the TRNSYS Simulation Studio. We can export the model by clicking on the Export to TRNBuild icon in the TRNSYS toolbar. We can also save the model as an IDF file, which is a standard format for exchanging building information among different software tools. In the TRNSYS Simulation Studio, we can integrate the building model with other TRNSYS components, such as heating and cooling systems, renewable energy systems, control strategies, etc. We can also run the simulation and view the results using the TRNSYS Simulation Studio.

8.2.4 TRNSYS

TRNSYS 17 is a comprehensive software package utilized globally by researchers and engineers for simulating transient systems, encompassing energy, thermal, and electrical domains. Featuring a user-friendly graphical interface known as TRNSYS Simulation Studio, it boasts a vast library of components spanning various system parts. This versatile tool incorporates a flexible engine capable of managing complex control strategies, along with multiple add-ons catering to specific tasks like integration with SketchUp and generating multizone building models. Operating on a modular approach, TRNSYS enables users to model transient system behavior by interconnecting individual components, each represented by a separate file known as a type. Through this methodology, users specify inputs, outputs, parameters, and controls for each component, allowing TRNSYS to execute simulation projects and present results in diverse formats. Overall, TRNSYS 17 emerges as a powerful solution for modeling and analyzing dynamic systems, serving as an indispensable tool in various applications such as solar systems, low-energy buildings, renewable energy systems, cogeneration, and fuel cells [310].

The TRNSYS interface is a user-friendly platform designed for creating, configuring, executing, and analyzing simulation projects. It features the TRNSYS Simulation Studio, which provides a graphical environment for users to interact with the software effortlessly. Within the Simulation Studio, users can manipulate simulation parameters and settings visually, enhancing productivity and ease of use. The interface boasts an extensive library of components covering various system elements, allowing users to accurately represent system behavior. Additionally, it offers tools for data visualization and analysis, enabling users to analyze simulation results comprehensively. One notable aspect of the TRNSYS interface is its intuitive design, making it accessible to users with varying levels of expertise. Figure 8-16 illustrates the layout and features of the TRNSYS interface, showcasing its user-friendly design and functionality.

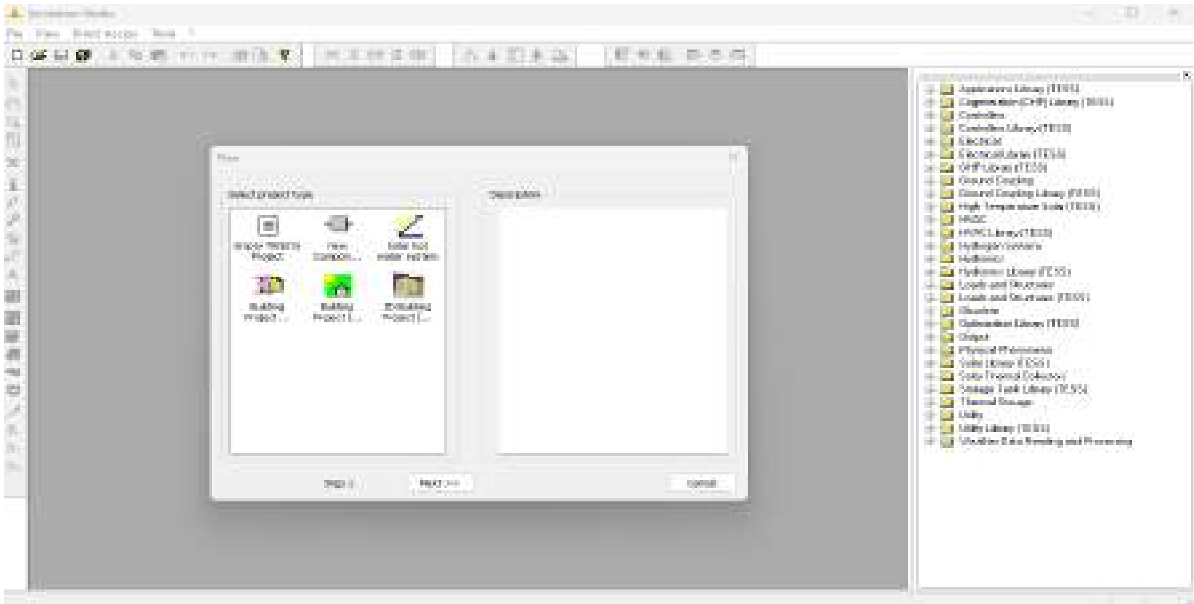


Figure 8-16 Illustration of the TRNSYS Interface

TRNBuild is a specialized graphical interface within the TRNSYS environment, dedicated to the creation and editing of multizone building models. This interface provides users with a range of tools and features tailored specifically for the design and simulation of complex building structures. With TRNBuild, users can efficiently develop detailed building geometries, define zones and surfaces, specify thermal properties and boundary conditions, and incorporate various building elements such as windows, doors, shading devices, and HVAC systems. The interface offers a user-friendly environment with intuitive tools for navigating and manipulating building components, enabling users to create accurate and customizable building models. TRNBuild plays a crucial role in the simulation workflow, allowing users to seamlessly transition from building design to performance analysis within the TRNSYS simulation environment [310].

Figure 8-17 displays the graphical interface of TRNBuild, a specialized tool within the TRNSYS suite for creating and refining multizone building models. In this interface, users can define the properties of walls, layers, materials, ventilation, infiltration, gains, radiant ceilings and floors, and occupants for comfort calculations. TRNBuild streamlines the process of building model creation by offering intuitive tools for component definition and zone specification. Additionally, it generates an information file compatible with the TRNSYS simulation engine, facilitating seamless integration into the simulation workflow. Notable features of TRNBuild include its user-friendly graphical interface, support for multiple languages and units, compatibility with various data formats such as

IDF, gbXML, and TRNBuild XML, as well as its ability to perform calculations and checks on building data. Moreover, TRNBuild enables the generation of reports and graphs summarizing both building data and simulation results, enhancing the analysis capabilities within the TRNSYS environment.

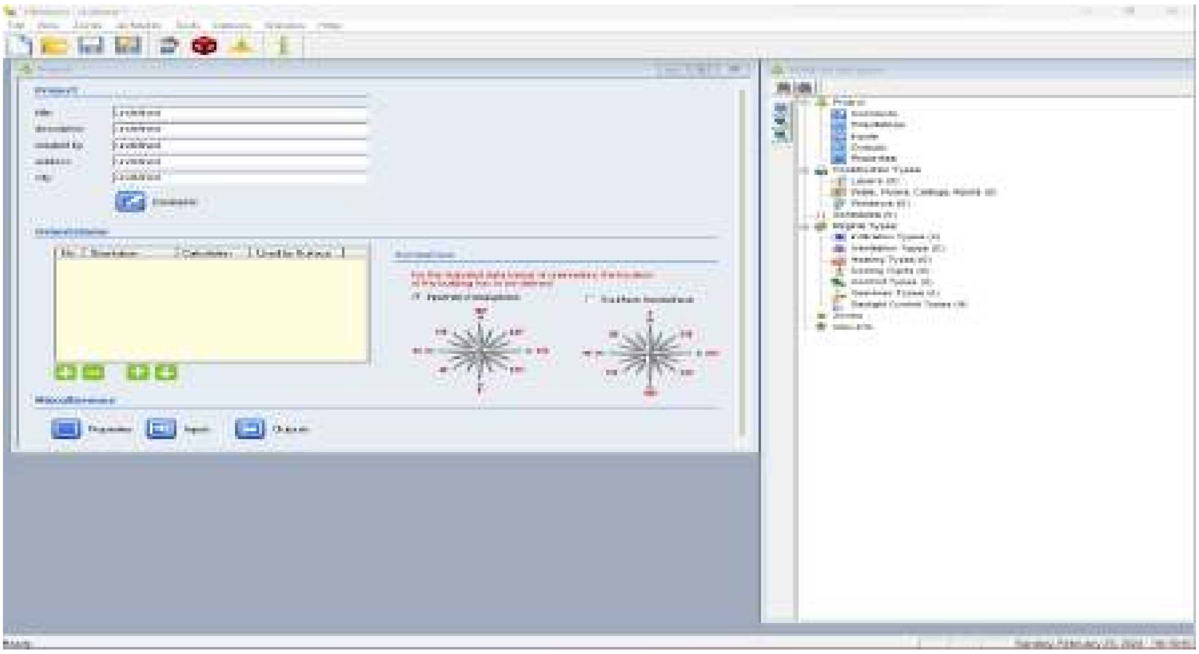


Figure 8-17 Graphical interface of TRNBuild

8.3 Appendix III: Climatic characteristics of the studied village

8.3.1 Appendix III-1: Weather data summary of the village khoualed Abdel Hakem, Ain Temouchent Wilaya

Month	January	February	March	April	May	June	July	August	September	October	November	December	Units
Global Horizontal Radiation (Average Hourly)	298	372	591	641	778	742	656	670	556	460	303	263	[Wh/m²]
Direct Normal Radiation (Average Hourly)	470	419	438	462	457	511	568	515	506	460	495	444	[Wh/m²]
Diffuse Radiation (Average Hourly)	97	124	160	165	180	172	150	162	151	134	99	88	[Wh/m²]
Global Horizontal Radiation (Max Hourly)	628	733	897	979	974	1002	1027	948	912	806	712	562	[Wh/m²]
Direct Normal Radiation (Max Hourly)	940	955	932	976	971	876	929	880	930	968	972	961	[Wh/m²]
Diffuse Radiation (Max Hourly)	297	347	394	453	495	501	346	430	446	378	299	265	[Wh/m²]
Global Horizontal Radiation (Average Daily Total)	2959	3592	4884	6061	6906	7529	7788	6881	5605	4259	3272	2645	[Wh/m²]
Direct Normal Radiation (Average Daily Total)	4660	4459	5155	5999	6355	7337	8018	6851	6177	5089	5016	4286	[Wh/m²]
Diffuse Radiation (Average Daily Total)	960	1328	1906	2137	2509	2471	2115	2159	1853	1485	1008	849	[Wh/m²]
Global Horizontal Illumination (Average Hourly)	31965	36301	44544	50600	54291	57891	61065	57721	50831	42435	35183	29663	[Lux]
Direct Normal Illumination (Average Hourly)	42100	39251	39758	43765	42369	47016	54357	48354	47398	42405	46019	41047	[Lux]
Dry Bulb Temperature (Average Monthly)	13	14	15	16	19	22	26	26	23	21	17	14	[°C]
Dew Point Temperature (Average Monthly)	9	9	11	12	15	18	20	22	20	17	12	10	[°C]
Relative Humidity (Average Monthly)	76	76	76	78	79	79	73	76	80	79	73	76	[%]
Wind Direction (Monthly Mode)	260	250	80	250	100	60	80	70	240	100	70	270	[Degrees]
Ground Temperature (Average Monthly of 1 Depths)	18	17	16	17	18	20	22	23	24	23	22	20	[°C]

8.3.2 Appendix III-2: Climatic characteristics of the studied village khoualed Abdel Hakem, Ain Temouchent Wilaya

Figure A: Map of Algeria highlighting the Wilaya of Ain Temouchent.

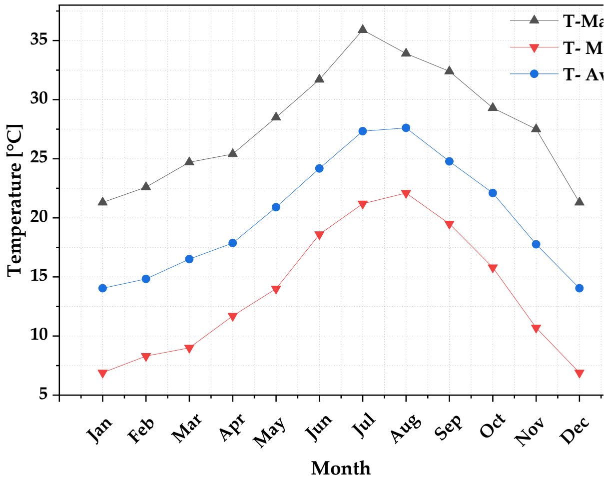


Figure B: Average monthly of ambient temperature.

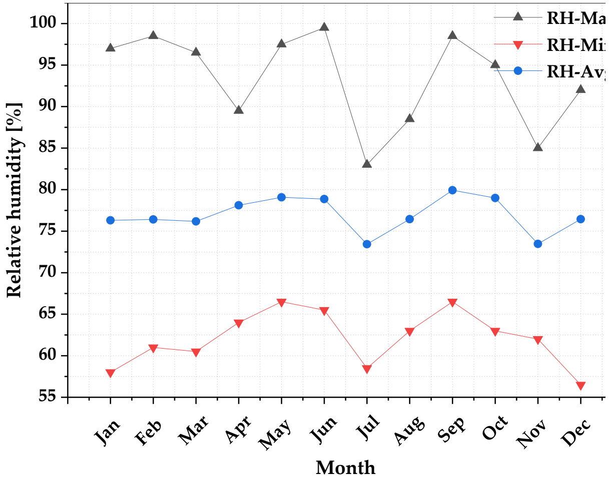


Figure C: Average monthly of relative humidity.

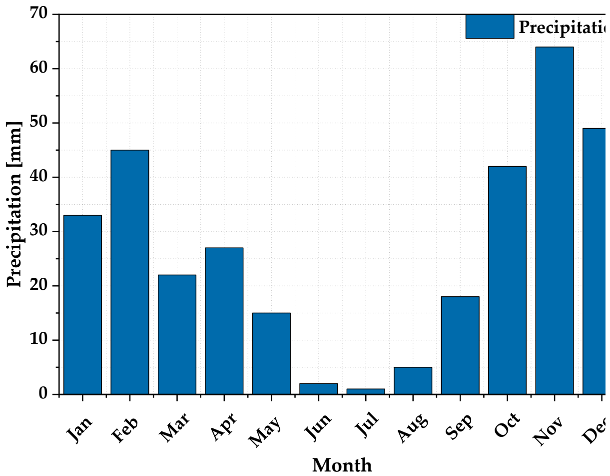


Figure D: Average monthly of precipitation.

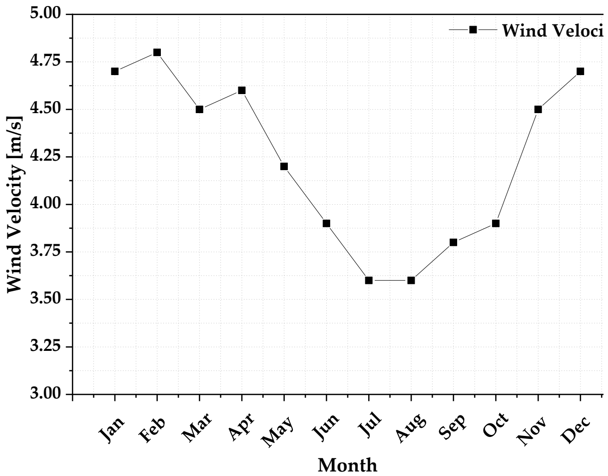


Figure E: Average monthly of wind Velocity.

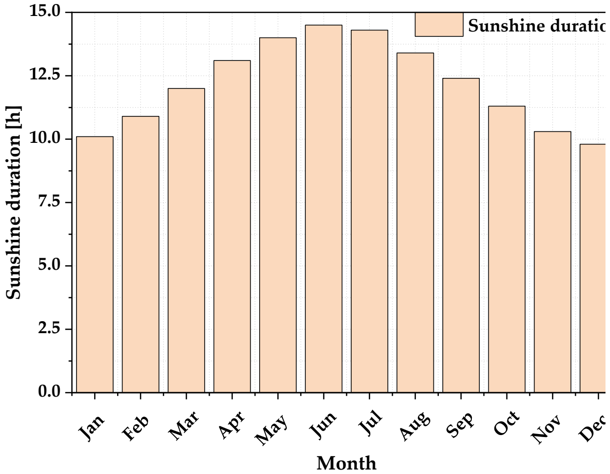


Figure F: Average monthly of sunshine duration

8.3.3 Appendix III-3: Design guidelines

Assuming only the design strategies that were selected on the Psychrometric Chart, 100.0% of the hours will be Comfortable. This list of Non-Residential design guidelines applies specifically to this particular climate. For each month, mentioned 20 design strategies arranged in order of importance. The 4th column, is for the selected design strategies for the whole year [309].

N°	*Months*	*Order of necessity*		*Design strategy according to Psychrometric Chart (to provide 100% of comfortable hours for each month)*
		Monthly, respectively	*Yearly*	
1	*Jan, Feb, Mar, Apr, May, Nov, Dec*	*8,9,11,11,14,10,9*	*19*	*Lower the indoor comfort temperature at night to reduce heating energy consumption (lower thermostat heating setback).*
2	*Jan, Feb*	*18,19*		*Extra insulation (super insulation) might prove cost-effective and will increase occupant comfort by keeping indoor temperatures more uniform.*
3	*Jan, Feb, Mar, Apr, Nov, Dec*	*6,5,8,9,8,6*	*16*	*Sunny wind-protected outdoor spaces can extend occupied areas in cool weather (enclosed patios, courtyards or verandas).*
4	*Jan, Feb, Mar, Nov, Dec*	*3,3,6,5,4*		*Glazing should minimize conductive loss and gain (minimize U-factor) because passive solar radiation gain or loss has less impact in this climate.*
5	*Jan, Feb, Mar, Apr, May, Nov, Dec*	*1,1,1,2,8,1,1*	*1*	*Heat gain from lights, occupants, and equipment greatly reduces heating needs so keep the building tight, well-insulated (to lower balance point temperature).*
6	*Jan, Feb, Mar, Apr, May, Nov, Dec*	*19,18,18,19,8,18,18*		*Insulating blinds, heavy draperies, or operable window shutters will help reduce winter night time heat losses if automatically controlled.*
7	*Jan, Feb, Mar, May, Nov, Dec,*	*20,20,20,18,20,19*		*Locate storage areas or garages on the side of the building facing the coldest wind to help insulate.*
8	*Jan, Feb*	*16,16*		*High-efficiency heaters or boilers (at least Energy Star) should prove cost-effective in this climate.*
9	*Jan, Feb, Mar, Apr, Jun, Sep, Nov, Dec*	*14,14,15,18,19,20,19,14*		*Trees (neither conifer or deciduous) should not be planted in front of a passive solar window, but are Ok beyond 45 degrees from each corner.*
10	*Jun, Jul, Aug, Sep, Oct*	*4,5,7,4,11*	*9*	*Use plant material (bushes, trees, ivy-covered walls) especially on the west to minimize heat gain (if summer rains support native plant growth).*
11	*Jan, Feb, Jul, Aug, Sep*	*17,17,19,16,16*		*Keep the building small (right-sized) because excessive floor area wastes heating, cooling, and lighting energy.*
12	*Jan, Feb, Mar, Apr, May, Jun, Oct, Nov, Dec*	*4,7,7,7,7,17,14,9,8*	*4*	*For the passive solar heating face, most of the glass area south to maximize winter sun exposure, and design overhangs to fully shaded in summer.*
13	*Apr, May, Jun*	*8,11,14*	*14*	*Provide double pane high-performance glazing (Low-E) on west, north and east, but clear on south for maximize passive solar gain.*
14	*Jan, Feb, Mar, Dec*	*15,15,19,15*		*Super tight buildings need a fan-powered HRV or ERV (Heat or Energy Recovery Ventilator) to ensure indoor air quality while conserving energy.*
15	*Jan, Feb, Mar, Apr, Nov, Dec*	*12,12,12,14,14,12*		*Small well-insulated skylights (less than 3% of floor area in clear climate, 5% in overcast) reduce daytime lighting energy and cooling loads. 23*
16	*Jan, Feb, Mar, Apr, May, Nov, Dec*	*5,6,5,5,10,7,7*	*12*	*Use high mass interior surfaces like slab floors and high mass walls to store winter passive heat and summer*

				night 'coolth'.
17	May, Jun, Jul, Aug, Sep, Oct	17,7,16,17,7,9	15	In wet climates, well-ventilated pitched roofs work well to shed rain and can be extended to protect entries, outdoor porches, and outdoor work areas.
18	Jul, Aug, Sep	11,10,18		A radiant barrier (shiny foil) will help reduce radiated heat gain through the roof in hot climates.
19	Jun, Jul, Aug, Sept	12,17,18,9		If soil is moist, raise the building high above the ground to minimize dampness and maximize natural ventilation underneath the building.
20	Jan, Feb, Mar, Dec	13,13,16,13		Windows can be unshaded and face in any direction because any passive solar gain is a benefit, and there is a little danger of overheating.
21	Jul, Aug, Sep	7,6,10		High-performance glazing on all orientations should prove cost-effective (Low-E, insulated frames) in hot clear summer or dark overcast winters.
22	Jan, Feb, Mar, Apr, May, Oct, Nov, Dec	10,10,10,10,9,18,11,11	20	Organize floorplan so winter sun penetrates into daytime use spaces with specific functions that coincide with solar orientation.
23	Jun, Jul, Aug, Sep, Oct	11,6,5,8,13,		minimize or eliminate west-facing glazing to reduce summer and fall afternoon heat gain.
24	Apr, May, Jun, Jul, Aug, Sep, Oct, Nov	17,5,9,13,15,12,5,15	11	Long narrow building floorplan can help maximize cross-ventilation in temperate and hot humid climates.
25	Apr, May, Jun, Jul, Aug, Sep, Oct, Nov	16,6,8,12,14,11,4,16	10	Good natural ventilation can reduce or eliminate air conditioning in warm weather if windows are well shaded and oriented to prevailing breezes.
26	Oct	20		To facilitate cross-ventilation, locate door and window openings on opposite sides of the building with larger openings facing upwind if possible.
27	May, Jun, Jul, Aug, Sep, Oct	20,5,4,4,5,15	7	Window overhangs (designed for this altitude) or operable sunshades (awnings that extend in summer) can reduce or eliminate air conditioning.
28	Jun, Jul, Aug, Sep	18,8,8,17	18	Raise the indoor comfort thermostat setpoint to reduce air conditioning energy consumption (especially if occupants wear seasonally appropriate clothing).
29	Mar, Apr, Dec	17,20,20		A whole-house fan or natural ventilation can store night-time 'coolth' in high mass interior surfaces (night flushing), to reduce or eliminate air conditioning.
30	Mar, Apr, May, Nov, Dec	13,13,16,13,16		High mass interior surfaces (tile, slate, brick or adobe) feel naturally cool on hot days and can reduce day-to-night temperature swings.
31	Mar, Apr, May, Oct, Nov, Dec	14,12,12,17,12,17		The best high mass walls use exterior insulation (like EIFS foam) and expose the mass on the interior or add plaster or direct contact dry-wall.
32	Jun, Jul, Aug, Sep	15,18,19,16		on hot days ceiling fans or indoor air, motion can make it seem cooler by 2.8 degrees C or more, thus, less air conditioning is needed.
33	May, Jun, Jul, Aug, Sep, Oct	15,13,14,13,14,12	17	Use light coloured building materials and cool roofs (with high emissivity to minimize conducted heat gain).
34	Jun, Jul, Aug, Sep, Oct	16,15,12,15,16		A High-Efficiency air conditioner or heat pump (at least Energy Star) Should prove cost-effective in this climate.
35	Jun, Oct	20,19		Use open-plan interiors to promote natural cross-ventilation, or use louvre doors, or instead use jump ducts if privacy is required.
36	May, Jun, Jul, Aug, Sep, Oct	13,10,20,20,13,10		Shaded outdoor buffer zones (porch, patio, lanai) oriented to the prevailing breezes can extend occupancy spaces in warm or humid weather.
37	Jan, Feb, Mar, Apr, May, Oct, Nov, Dec	11,11,9,6,3,7,6,10	13	Low pitched roofs with wide overhangs work well in temperate climates.
38	Apr, May, Jun, Jul, Aug, Sep, Oct, Nov	15,4,1,9,11,3,1,17	6	Screened occupancy areas and patios can provide passive comfort cooling by ventilation in warm weather and can prevent insect problems.
39	Jul, Aug, Sep	10,9,19		Orient most of the glass to the north, shaded by vertical fins, in very hot climates, because there are

				essentially no passive solar needs.
40	*Jan, Feb, Mar, Apr, May, Oct, Nov, Dec*	*7,4,2,1,1,3,2,2*	*8*	*This is one of the comfortable climates, so shaded to prevent overheating, open breezes in summer, and use passive solar gain in winter.*
41	*Jun, Jul, Aug, Sep, Oct*	*6,1,1,6,8*	*3*	*In this climate air conditioning will always be needed but can be greatly reduced if building design minimizes overheating.*
42	*Feb, Mar, Apr, May, Oct, Nov*	*8,4,3,2,2,3*	*2*	*climate responsive buildings in temperate climate used lightweight construction with slab on grade and operable walls shaded outdoor spaces.*
43	*Jan, Feb, Mar, Apr, Nov, Dec*	*2,2,3,4,4,3*		*Climate responsive buildings in cool overcast climates used low mass tightly, well-insulated construction to provide rapid heat building in morning.*
44	*Jun, Jul, Aug, Sep*	*3,3,3,2*		*climate responsive buildings in warm humid climates used lightweight construction with operable (French) windows protected by deep overhangs and verandas.*
45	*Jan*	*9*		*Climate responsive buildings in cold clear climate has a snug floorplan with central heat source, south-facing windows, and roof pitched for wind protection.*
46	*May, Jun, Jul, Aug, Sep, Oct, Dec*	*19,2,2,2,1,6,5*	*6*	*Climate responsive buildings in hot humid climates used lightweight construction with openable walls and shaded outdoor areas, raised above the ground.*

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