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RÉSUMÉ

Architecture bioclimatique et climat chaud extrême - développements et expérimentations de stratégies actives et passives

Cette étude examine le potentiel de l'architecture bioclimatique dans les climats extrêmement chauds, en se concentrant sur le prototype BaityKool développé pour le Solar Decathlon Middle East 2018. Conçu pour s'adapter à l'environnement de Dubaï, ce prototype fonctionne désormais comme un laboratoire vivant, testant des stratégies de conception éco-responsables avec des systèmes passifs et actifs pour atteindre le confort thermique et réduire la consommation d'énergie. Des expériences ont été menées sur différentes saisons afin d'évaluer des stratégies telles que la protection solaire, la ventilation naturelle, leur combinaison et l'ombrage des terrasses. Ces expériences ont visé à démontrer comment la baisse de la température intérieure peut diminuer la demande énergétique pour le refroidissement et améliorer le confort des occupants. En été, trois types de rideaux dynamiques ont été installés sur les fenêtres et portes vitrées orientées à l'est et à l'ouest afin de réduire les apports solaires. Les tests de ventilation naturelle ont permis d'évaluer le potentiel de refroidissement gratuit grâce à la circulation d'air diurne et nocturne en hiver et pendant les saisons de transition (été-hiver et hiver-été). La combinaison de la protection solaire et de la ventilation nocturne vise à améliorer le confort thermique intérieur des occupants pendant les périodes de transition en bloquant le rayonnement solaire pendant la journée et en dissipant la chaleur la nuit. Le patio intérieur, avec son agencement et son orientation stratégiques, sa végétation et sa pergola solaire, a été évalué pour déterminer sa performance, notamment en tant qu'habitat bioclimatique. Enfin, la performance du système d'enveloppe sans rideaux d'ombrage a été évaluée afin de déterminer sa capacité à abaisser la température intérieure par rapport à la température extérieure, réduisant ainsi les fluctuations de température par des moyens passifs.

L'étude a visé : (i) à explorer le potentiel de l'architecture bioclimatique dans les climats extrêmement chauds, (ii) à évaluer les avantages de ces approches et (iii) à évaluer la faisabilité d'atteindre le confort thermique des occupants grâce à une combinaison de stratégies passives et actives, afin de réduire la demande énergétique pour le refroidissement dans différents scénarios.

Mots-clés : Architecture bioclimatique, climat extrêmement chaud, expérimentations, stratégie passive et active, confort thermique.

ABSTRACT

Bioclimatic Architecture and Extreme Hot Climates – Developments and Experimentation of Active and Passive Strategies

This study investigates the potential of bioclimatic architecture in extremely hot climates, focusing on the BaityKool prototype developed for the Solar Decathlon Middle East 2018. Designed to adapt to the environmental conditions of Dubai, this prototype now serves as a living laboratory for testing eco-responsible design strategies integrating passive and active systems to achieve thermal comfort while reducing energy consumption. Experimental campaigns were conducted across different seasons to evaluate strategies such as solar protection, natural ventilation, their combination, and terrace shading. These experiments aimed to demonstrate how lowering indoor temperatures can reduce cooling energy demand and improve occupant comfort.

During summer, three types of dynamic shading curtains were installed on east- and west-facing glazed openings to reduce solar gains. Natural ventilation tests assessed the potential for free cooling through daytime and nighttime airflow during winter and transitional seasons (summer-winter and winter-summer). The combination of solar protection and night ventilation aimed to enhance indoor thermal comfort during transition periods by blocking solar radiation during the day and dissipating heat at night. The inner courtyard characterized by its strategic layout and orientation, vegetation, and solar pergola was evaluated to determine its performance, particularly as a bioclimatic habitat. Finally, the performance of the envelope system without shading curtains was assessed to determine its ability to lower indoor temperature relative to outdoor conditions, thereby reducing temperature fluctuations through passive means.

The objectives of this study were: (i) to explore the potential of bioclimatic architecture in extremely hot climates, (ii) to assess the benefits of these approaches, and (iii) to evaluate the feasibility of achieving occupant thermal comfort through a combination of passive and active strategies, in order to reduce cooling energy demand under various scenarios.

Keywords: Bioclimatic architecture, extreme hot climate, experimental study, passive and active strategies, thermal comfort

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NOMENCLATURE

Latin letters

A	Area	(m2)
C	Convective Heat	(W/m2)
d	Diameter	(m)
e	Emitted Heat	(W)
E	Evaporative Heat	(W/m2)
g	Black Globe	(-)
h	Heat Transfer Coefficient	(W/m2 °C)
H	Irradiance	(W/m2)
K	Psychological coefficient	(°C-1)
L	Heat loss from the body	(W/m2)
P	Vapor pressure	(kPa)
q	Heat per unit surface area	(W/m2)
Q	Heat Transfer loss/gain	(W/m2)
R	Radiant Heat	(W/m2)
T	Temperature	(°C)
V	Velocity	(m/s)
X	Physiological Factors	(-)
Y	Psychological Factors	(-)

Greek letters

α	Thermal absorptivity	(-)
ε	Emissivity	(-)
η	Adaptive coefficient/factor	(-)
ρ	Thermal reflectivity	(-)
φ	Heat flux density	(W/m2)
Φ	Heat flow	(W)

Subscripts and Superscripts

a	Ambient Air
b	Black Body
b	Back
c	Convection
cr	Core
comf	Comfort
conv	Convection
cl	Clothing
d	Down
diff	Diffusion
dry	Dry
eff	Effective
Evap	Evaporation
Exp	Experiment
f	Front
g	Globe

i	Direction
l	Left
m	Mean
mrt	Mean Radiant Temperature
n	Neutral
n	Number
net	Net
o	At rest
op	Operative
out	Outdoor
pr	Plane radiant
r	Radiant
r	Right
rad	Radiation
res	Respiratory
s	Surface
sa	Saturated
sk	Skin
skr	Skin temperature required at thermal comfort
sw	Sweating
u	Up
td	Duration
vap	Vapor

Abbreviations

AA	Architectural Action	(-)
ACS	Adaptive Comfort Standard	(-)
AH	Absolute Humidity	(g/kg)
Aqu	Aquaponics	(-)
BEA	Building Efficiency Accelerator	(-)
BIPV	Building Integrated Photovoltaics	(-)
BRm	Bedroom	(-)
CFD	Computational Fluid Dynamics	(-)
Clo	Clothing Resistance	(clo)
Day	Day	(-)
DBT	Dry Bulb Temperature	(°C)
DM	Dubai Municipality	(-)
DV	Day Ventilation	(-)
DOE	Design of Experiments	(-)
Dr	Door	(-)
east	East	(-)
ext	External	(-)
Exp	Experiment	(-)
ETC	External Translucent Curtain	(-)
Fluc	Fluctuation	(-)

GBRS	Green Building Regulation and Specification	(-)
GEF	Graphic Evaluative Framework	(-)
GT	Globe Temperature	(-)
HVAC	Heating Ventilation and Air Conditioning	(-)
int	Internal	(-)
IRENA	International Renewable Energy Agency	(-)
ITC	Internal Translucent Curtain	(-)
Kit	Kitchen	(-)
Liv	Living	(-)
MST	Mean Skin Temperature (34°C)	(°C)
MRT	Mean Radiant Temperature	(°C)
Nt	Night	(-)
north	North	(-)
Nu	Neutral	(-)
Nat V	Naturally Ventilated	(-)
NV	Night Ventilation	(-)
Pat	Patio	(-)
PLY TPO	Single-ply roofing membrane – Thermoplastic Polyolefin	
PMV	Predicted Mean Vote	(-)
PMVe	Predicted Mean Vote with expectancy factor	(-)
Psych	Psychology	(-)
PV	Photovoltaic	(-)
RBB	Roller Blind Blackout	(-)
Ref	Reference	(-)
RH	Relative Humidity	(%)
Rf	Roof	(-)
SDME	Solar Decathlon Middle East	(-)
south	South	(-)
SSC	Solar Shading Curtain	(-)
SH	Saturation Humidity	(g/kg)
SKBF	Skin Blood Flow	L/hrm2
SMT	Skin Mean Temperature	(°C)
SS	Solar Shading	(-)
TRm	Technical room	(-)
TS	Thermal Sensation	(-)
TSC	The Sustainable City	(-)
TSV	Thermal Sensational Vote	(-)
UHPC	Ultra High Performance Concrete	(-)
Ven	Ventilator	(-)
Veg	Vegetation	(-)
WRm	Washroom	(-)
wall	Wall	(-)
west	West	(-)

General Introduction

INTRODUCTION

A building design must create a shelter for its occupants, achieving good thermal comfort while utilizing energy efficiently and optimally. A major challenge for the countries in the Arabian Peninsula and the Gulf is the hot, arid climate and the rising energy demand. Buildings here consume about 80 percent of the electricity generated and are used for air conditioning [1]. The rapidly growing, modernized, and urbanized Middle East is influenced by Western architectural design and construction ideologies [2]. Architectural practice must consider energy efficiency, thermal comfort, and adaptive ventilation strategies that encourage active occupant behavior. Recent studies have emphasized the importance of designing buildings with reduced reliance on artificial heating and cooling, thereby ensuring a healthy indoor environment for occupants [3]. The architectural design strategies and construction technology presently adopted do not consider the place's local context or the desirable weather conditions. Buildings in the United Arab Emirates (UAE) region are primarily designed with sealed window openings and fixed glazing, which are dependent fully on-air conditioning systems to achieve thermal comfort at all seasons. Buildings are highly energy-intensive, with the majority of the electric energy produced by burning diesel oil and natural gas. The UAE has the world's highest carbon emissions per capita, 21.6 tons per person in 2023 [4]. Several factors contributing to this are the construction boom, the availability of cheap energy prices in the UAE compared to advanced countries, and a lack of green building practices [5].

The UAE residential construction market accounted for the largest share of the construction market in 2023, with an average annual growth rate (AAGR) of 3% predicted. The residential project types comprise single- and multi-family housing, reflecting a growing demand in the housing sector development due to the UAE's increasing status as a global business hub and luxury living destination, as well as changing government policies that attract public and private sector investors [6]. According to the International Renewable Energy Agency (IRENA), renewable energy prospects have become economically attractive, with renewable energy accounting for 10% of the country's total energy mix as of 2023.

There are growth prospects in the future, with the government encouraging the use of clean energy through its Energy Strategy 2050. The COP 28 global renewal and energy efficiency pledge recognized the crucial need to accelerate improvements in efficiency, energy security, and

affordability. A collective commitment was made to achieve a global average annual rate of improvement from 2% to 4% by 2030 [7]. The movement towards energy-efficient buildings in Europe and North America emerged in the 1970s and 1980s, following the energy crisis of the 1970s. In the Middle East, traditional architecture presented environmental responses to the region's hot and arid climate, which was overshadowed during colonial times. With the onset of the post-colonial period, a strong national identity demanded the construction of buildings that reflected heritage. By the mid-19th century, the Middle East was flooded with Western ideas. In the significantly altered urban settlements, traditional courtyard houses began to disappear as new construction of independent single-family houses became prevalent, which was unsuitable for the harsh climate. The new architecture adhered to the international style, incorporating new materials and technologies. Over the past 20 years, energy-efficient designs in the Middle East have been developed in Western and European styles, and high-tech, expensive building strategies with extensive glazing systems do not suit the region's climate [8].

In the present day, the concepts of climate change and sustainability have led the Middle East to global cooperation. In 2021, the UAE signed the Paris Agreement, announcing the target to reach net zero by 2025, and hosted the 2023 COP28 of the United Nations Framework Convention on Climate Change (UNFCCC). The third update of the second nationally determined contribution of the UAE submitted to UNFCC shows the building sector responsible for 27% of greenhouse gas emissions in the UAE as of 2019, but also shows the opportunity for emission reduction by 56% by 2030, making the building sector critical to meet the net-zero target by 2050. The UAE Sustainable Built Environment Blueprint Report outlines key findings, policies, and priority areas identified by the Ministry, aiming to reduce 43 metric tons of carbon dioxide equivalent (MtCO2e) by 2023. The Race to Zero Campaign has 48% of major Architects and Engineers, 19% of construction companies, and 27% of cities that have committed to unified actions [9]. The Sustainability agenda emphasizes carbon emissions and the maintenance of human welfare with economic growth. High domestic energy and water consumption and a desire for environmental awareness drive sustainable education and practice. External pressure from commercial developers with rapid urbanization, growing need, and high demand for domestic energy generated from the natural oil resource, puts strain on a stable economy and energy infrastructure. The government aims to create a diverse economy based on sustainable ideologies, persuading sustainable development for new projects to meet the growing energy demands [5].

General Introduction

Over the past few years, three approaches to sustainability have evolved. '**The Revivalist'** is a traditional approach that utilizes local and environmentally friendly materials and design strategies, including courtyards with microclimates, natural ventilation, shading, and evaporative cooling. **'The Progressive'** approach, with no use of the traditional design, seeks solutions with new technologies, energy-efficient digital technology, and high-spec glazing integrated with renewable energy systems. This approach is expensive and relies on a global supply chain solution. The UAE has adopted this approach over the past 20 years, utilizing high-tech, energy-efficient designs, despite its global architecture not being well-suited to the region's climate. The 21st century shows effort in the Middle East towards sustainable development, with **'the Hybrid'** approach a union of the two approaches (Fig. 1) [10]. This approach utilizes traditional methods, incorporating natural ventilation through wind towers and solar chimneys, to achieve a balanced shading and envelope insulation strategy. It leverages modern technology to create an efficient cooling system, ensuring good annual thermal comfort while minimizing environmental impacts. Examples are Siemens HQ, Masdar Institute for Science & Technology, and Abu Dhabi. IRENA HQ, Abu Dhabi & Pacific HQ, Dubai.

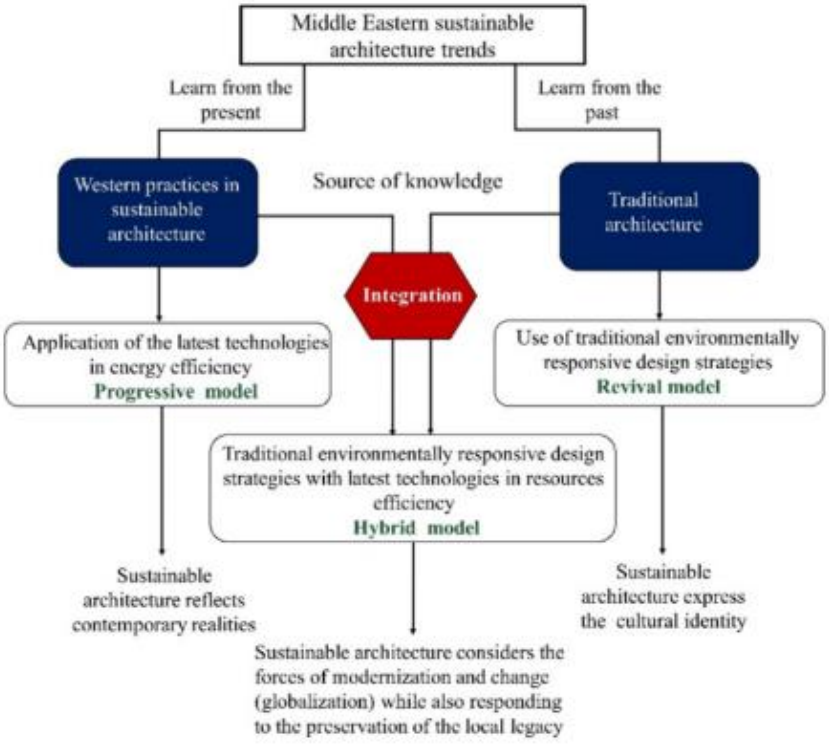


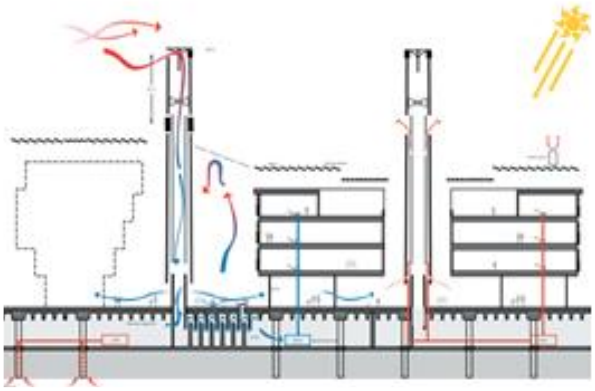
Figure 1: The sustainable housing trends and model in the Middle Eastern region based on Yahya and Hassanpour, [10].

General Introduction

Masdar City, as shown in Fig. 2(a), is a model of a sustainable mixed-use community powered by 100% renewable energy, aiming to become the world's first zero-carbon and zero-waste city. Designed with energy-efficient buildings with increased focus on natural ventilation and night cooling. A well-planned walkable neighborhood using reinterpretation of regions' traditional architecture, vernacular forms, and passive design strategies as represented on the sectional elevation in Fig. 2 (b).



(a)



(b)



(c)

Figure 2: (a) View of Masdar Institute, (b) Section of the Masdar Institute with Passive design strategies, (c) Sectional Elevation of the Campus living block with passive design strategies (Source: [11])

The wind tower is an inspiration from traditional Islamic architecture [12], capturing the upper-level winds and directing them to the open-air public spaces. A combination of evaporative cooling and air movement techniques helps moderate air temperature and improve personal comfort conditions. The thermal mass in walls features a red sand-colored undulating glass-reinforced concrete screen, which serves as a mashrabiya screen to modulate the temperature throughout the day, conserving energy with a higher set point [10]. The circulation areas 'climate lobbies' act as transitional zones maintained with warmer temperatures than the regularly occupied interior spaces and help prevent 'thermal shock' as one moves from intense heat to a cooler space, increasing the occupant's comfort. Fig. 2 (c) shows the solar shading using BIPV panels and overhangs in the living block with the perforations to minimize direct sunlight. Designed to use less than half the energy of buildings that comply with U.S energy standards, ASHRAE 90.1-2004 [13].

The International Renewable Energy Agency (IRENA) Headquarters, as shown in Fig. 3, is a 32,000 m². building located at Masdar, Abu Dhabi. This building has achieved the UAE Certification Estidama's first Four Pearls structure, measuring Energy, water, and carbon efficiency. An advanced building with passive design and smart energy management demands 42% less energy than the global energy-efficient standards and 64% less energy demand than a typical building in Abu Dhabi.

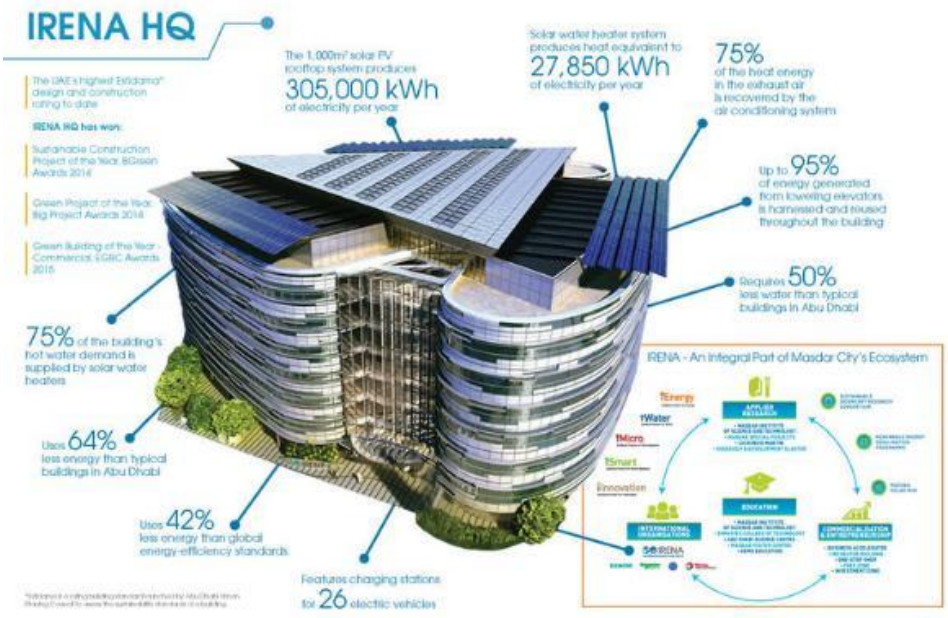


Figure 3: International Renewable Energy Agency (IRENA) Headquarters with UAE Certification Estidama, the first Four Pearls structure (Source: [14])

The complex uses 50% less water than a typical building in Abu Dhabi. The efficient envelope system is twice as air-tight as the Estidama requirements, resulting in reduced energy use. The air conditioning system cools the incoming fresh air by recovering 75% of the energy released through air exhaust. A green supply chain with low carbon and locally sourced sustainable materials used for construction [14].

Pacific HQ Dubai, the first LEED Platinum-rated green Building, as in Fig. 4, is among the 16 worldwide buildings for the grade completed in September 2006. It uses thermally efficient windows, walls, and roofs with energy-efficient HVAC working on Solar PV with absorption chillers and a lighting system capitalizing on daylight. A totally IP-enabled automation system integrated with a building for lighting, AV, HVAC, Fire alarm, security, access systems, lifts & STP. This enhances the system's reliability through operations and maintenance, resulting in increased service efficiency. The roof of the building is covered with BIPV, providing energy for lighting, and 25% of the 400-tonne air conditioning power is out, and 100% of the water used in the building is recycled [15]. There is a need to create adaptive design strategies with a strong cultural identity and a manifestation of global sustainability understood locally [2].



Figure 4: Pacific HQ Dubai, the first LEED Platinum-rated green Building, UAE (Source: www.pacific-controls-systems-llc)

Vernacular houses in the Middle East exemplify sustainable architecture, utilizing design strategies and construction technologies that manage temperature, humidity, natural ventilation,

and light. The traditional passive design concepts and values of vernacular architecture had climate-responsive solutions for both architecture and urban design, offering comfortable indoor places during the hot weather with the passive design solutions like courtyards and wind catchers 'Barajeel' with great resilience on electrical support for improving thermal comfort.

Sadly, the passive design strategies, as shown in Fig. 5 (a), (b) and (c), which were used in traditional buildings at Al Bastakiya Dubai in the hot arid climate, were ignored after the discovery of oil to generate energy for the chillers. Studies show that 70% of electricity consumption in residential buildings is used by chillers, which contribute to a greater heat island effect, higher pollution, and increased outdoor temperatures in the urban fabric.



(a) (b) (c)

Figure 5: (a) View of ventilated corridors b) View of shaded walkways c) View of shaded courtyards (Source: Google Images Historical Neighborhood Al Bastakiya, Dubai)

Traditional Arabic architecture in Al Bastakiya, Dubai, employs passive design strategies, including shaded walkways, wind towers, and courtyards. The UAE is among the countries with the highest impact on climate change, with summer temperatures reaching up to 55 degrees [16]. Construction techniques in residential buildings have improved, with thermal comfort achieved through air conditioning, which consumes significant amounts of electricity and natural resources. Saeed Al Abbar, Chairman of the Emirates Green Building Council, stated at the Emirates Energy Efficiency Summit 2016 in Dubai that the UAE's energy consumption ranges from 220-360 kWh per square meter. Currently, a one-meter-per-year improvement is possible. Using appropriate design strategies can enhance energy efficiency by between 110 and 160 kWh per square meter.

Developing zero-energy buildings should be the goal for future developments in the built environment [14].

In 2019, Dubai became the first city in the Arab World, Middle East, and North Africa (MENA) region to receive LEED for Cities certification. Dubai Municipality (DM) applied the Green Building Regulation and Specification (GBR&S) to all government buildings by 2011, and it became mandatory for all new buildings by 2014. In 2016, DM introduced a four-level certification system to promote a sustainable built environment [17]. Technical guidelines were introduced in 2017 to retrofit existing buildings, aiming to reduce energy and water use by 30% by 2030 and achieve 75% clean energy contribution in the fuel mix by 2050 [15]. The Green Building Regulation, introduced by DM in 2010, was not a rating system but aligns with voluntary systems like LEED, BREEAM, and ESTIDAMA to meet sustainability requirements [16]. It emphasizes the quality and performance standards of materials and systems, including thermal comfort standards for active strategies utilizing HVAC systems, indoor air quality management, and handling hazardous materials, as well as envelope systems that meet safety and high-tech performance standards. In 2010, Abu Dhabi's Urban Planning Council (UPC) launched Estidama, the Arabic word for sustainability, with the Pearl Rating System (PRS) mandatory for all new buildings in Abu Dhabi, integrated into the building permit process. It promotes sustainable development rooted in local traditions, considering the region's harsh climate, and emphasizes passive strategies and recycled products to preserve and enhance residents' cultural identity and quality of life [17]. The two good adapters of sustainable nearly zero-energy residential projects are 'The Masdar City Eco-Villa' constructed at Abu Dhabi and 'The Sustainable City' with environment friendly community in Dubai. Both the houses have used high performance thermal envelops responding to the local climate. The building follows the Green Building Regulations Al Sa'fat which aims at enhancing the sustainability level of the buildings and reduce energy consumption by 30% [18].

The Sustainable city (TSC) designed as a live-work-thrive community, a low-carbon residence with 500 villas and 89 apartments using passive strategies, use of recycled materials and low-carbon products, and highly efficient systems. They consume 100 kWh/ m2 annually, which is 65% lower in electricity use intensity (EUI) compared to other similar villas in Dubai. The villas

also have solar PV canopies that generate 40% of their energy demand. villas also have solar PV canopies generating 40% of the energy demand [19], [20].

The Eco-Villa in Masdar provides a highly energy-efficient home that meets the needs of a typical Emirati family. Built with insulated concrete foam (ICF), most materials are locally sourced and include high-efficiency equipment along with energy management systems. They use 97 kWh/m² per year. The solar PV system produces up to 102% of the home's energy requirements [18], [21].

In 2015, Dubai's Supreme Council of Energy, Dubai Electricity & Water Authority (DEWA), and the U.S. Department of Energy signed an agreement to collaborate on the Solar Decathlon Middle East (SDME), a competition addressing sustainable living in the Middle East, tailored to local challenges such as heat, dust, and high humidity, while integrating regional characteristics. Since 2002, nine editions of the Solar Decathlon have been held in the United States, with expansions to Europe, China, Latin America, and the Middle East & Africa. The 24-month international architecture, design, and engineering competition began in October 2016, with the teams for SDME 2018 announced at the World Green Economy Summit (WGES) at Dubai International Convention and Exhibition Centre.

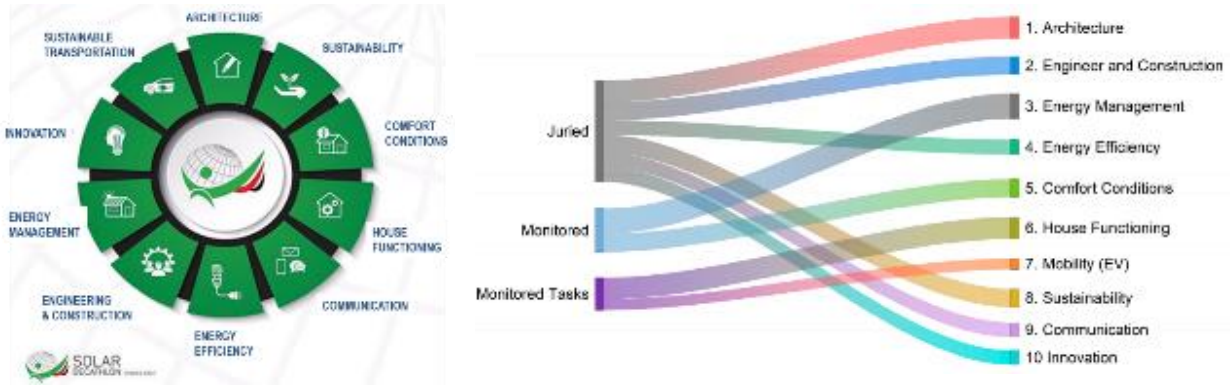
The selected SDME 2018 competing teams, as shown in Figure 6 (a) and (b), participated in the WGES 2016 at Dubai International Convention and Exhibition Centre. The final phase of house assembly, which included evaluation by an international jury of the functioning house, public tours, and monitoring of energy and environmental performance, took place between October 28 and December 8, 2018 [18].



(a) (b)

Figure 6: (a) SDME teams 2018 on WGES stage, (b) BaityKool Team introduction at WGES 2016, [22].

The first SDME was held in 2018 with eleven participating sustainable houses; the second SDME was held in 2021 with eight homes. The competition had test conducted of the functioning houses for 10 contests: architecture, engineering and building, energy management, energy efficiency, comfort conditions, house functioning, sustainable transport, sustainability, communications, and innovation, and in Figure 7 (a) with the assessment mode as indicated in Figure 7 (b).



(a) (b)

Figure 7: (a) The SDME competition contest criteria, (b) The contest assessment mode [18].

During the competition's testing period, the house assembled at the competition site, Mohammed bin Rashid Al Maktoum Solar Park in Dubai, as shown in Fig. 8, was open to the public for demonstrations, knowledge sharing, team meetings, and experiencing innovative systems.

http://www.baitykool.com/ (accessed July 14th, 2025)



Figure 8: SDME 2018 competition site at Mohammed bin Rashid Al Maktoum Solar Park, [19])

The Middle East has the fastest-growing urban population in the world, with an expanding construction industry facing high energy demand and greenhouse gas emissions. There is a need for strict building codes to ensure zero-energy buildings, which help maintain a secure energy supply from renewable sources and reduce carbon emissions from the built environment. The region's extremely hot, arid climate results in higher energy consumption due to mechanical systems used to keep indoor environments healthy and comfortable. A cost-effective way to achieve high energy performance is through the application of passive design strategies, starting with the proper design of building thermal envelopes. These strategies improve energy efficiency in buildings, thereby decreasing reliance on renewables to meet energy demands. The UAE government, along with federal and local agencies, has increased its focus on sustainable development, including efforts to improve building efficiency and revise regulatory energy conservation codes, working progressively toward a Nearly Zero Energy Building goal [19].

The positive outcomes of the SDME competition greatly contribute to scientific research on sustainable building models adaptable to climate [20]. This is a key step in fighting global warming and climate change, supporting the UAE Vision 2030 to increase the share of clean energy to 30% of total energy. The UAE's sustainability efforts align with the Energy Strategy 2050, which aims for a balanced supply and demand of energy, as part of the UAE Ministry's goal to achieve net zero by 2025 [21]. The SDME projects have demonstrated potential for sustainable zero-energy buildings suited for hot, arid climates. Material choices prioritize low environmental impact, incorporating energy conservation factors and the thermal performance of envelopes through passive design strategies such as self-shading and thermal mass. Results during the monitoring period showed that energy performance reached positive energy levels, surpassing nearly zero-energy early adopter houses at The Sustainable City and similar to those of the Eco-Villa at Abu Dhabi's Masdar City [19]. This creates an opportunity for Dubai Electricity and Water Authority (DEWA) to initiate processes related to the design, construction, operation, testing, and exploration of sustainable, energy-efficient, bioclimatic, eco-sensitive, and climate-responsive housing designs engineered for Dubai’s extreme warm climate. The DEWA Research and Development (R and D) Center at the Mohammed bin Rashid Al Maktoum Solar Park has become a global platform supported by the Enabler: Energy System Analyses for research activities aimed at fostering innovative and sustainable development, enhancing energy efficiency and conservation, and accelerating clean energy use in the built environment [22]. In his inaugural

speech, HE Saeed Mohammed Al Tayer, Vice Chairman of the Dubai Supreme Council of Energy and MD/CEO of DEWA, emphasized the UAE's role as a hub for creativity and innovation, showcasing smart homes that promote sustainable lifestyles through clean energy and cost-effective, energy-efficient solutions designed for the climate and environmental conditions of the Middle East.



(a) (b) (c)

Figure 9: (a) BaityKool Living Lab commissioned at The Sustainable City (TSC) Dubai, (b) the view of the green core patio (courtyard) from North West, (c) Interior view of the Living room at BaityKool Lab from the Kitchen at South (Source: Author)

The eco-responsive, self-sustaining, energy-efficient, innovative bioclimatic prototype BaityKool from the first edition of Solar Decathlon Middle East (SDME) 2018, as shown in Fig. 9, serves as an experimental lab to test the potential of bioclimatic design in Dubai's extremely warm climate.

The University of Bordeaux, France was the official leader of BaityKool project with an international, interdisciplinary and multi-actor framework with a network of active members: Academic Consortium composed of Université de Bordeaux, (France), Arts and Métiers Paris Tech, École Nationale Supérieure d'Arts et Métiers, France, ENSAP-Bx, École Nationale Supérieure d'Architecture et de Paysage de Bordeaux, France, Amity University in Dubai (United Arab Emirates), An-Najah National University in Naplouse (Palestine) Nobatek, a technological center for sustainable building, pilot of INEF4 Institute for energy transition, France as in Fig. 10.

Figure 10: The academic consortium of the BaityKool Team, [22].

General Introduction

A 105.5 m^2 unit, as shown in Figure 8, is a multi-family housing design adapted for extremely warm climates. It is suitable for densely populated urban areas and includes living and co-working spaces. The name BaityKool is derived from the Arabic word “Baity,” meaning in arabic ‘my house’ combined with “cool,” which means ‘fresh’, ‘calm’, and ‘pleasant’. The design addresses environmental complexity and sensitivity through a holistic approach, incorporating culture, nature, and technology. The prototype was developed using a trans-disciplinary method with a multi-cultural, interdisciplinary team of students, professors, faculty advisors, and industry professionals working together on design, construction, and assembly. The concept is a multifamily dwelling that can function as a living space and transform into a co-working area, suitable for traditional families and young entrepreneurs. The house is flexible enough to evolve with the needs of its inhabitants. Inspired by traditional medina housing, the design features an introverted layout with a courtyard, called “Fena,” arranged in a C-shaped form surrounding the inner mass. The design maximizes openings facing the courtyard and minimizes those on the exterior to improve environmental control. The envelope system, made of mineral materials with perforations inspired by classical mashrabiya, maintains comfort and privacy for the residents. The BaityKool prototype was designed and prefabricated in France and transported in containers to Dubai, UAE.

Figure 11 shows the working progress during the design phase, from brainstorming ideas to design detailing, assembly of the building elements and systems at Poitiers, France, and the first assembly of the prototype at the campus of Amity University Dubai between July and October 2018.

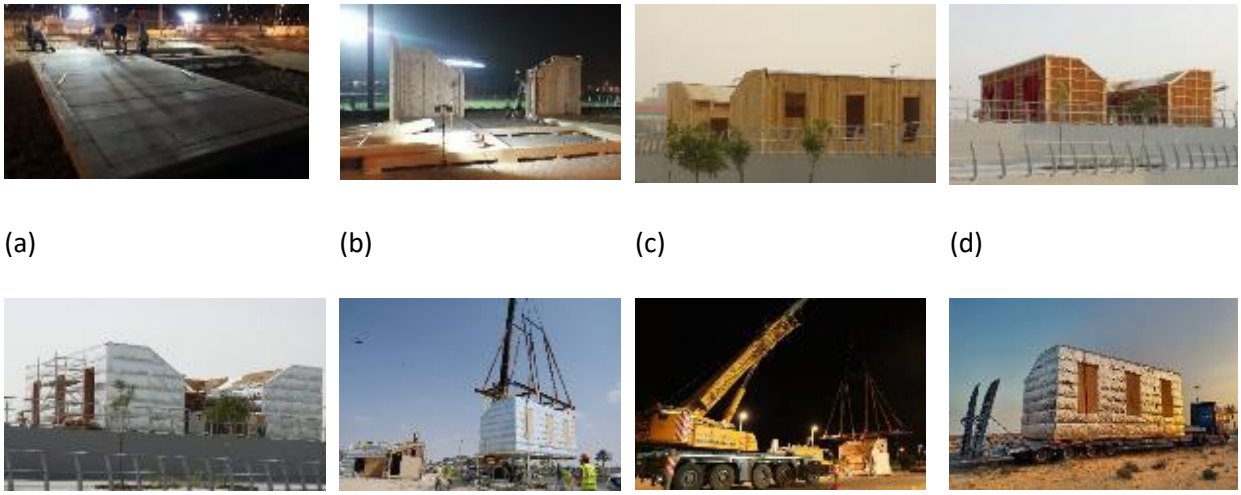


(a) (b) (c)



(d) (e) (f)

Figure 11: The working progress of BaityKool during the design phase at Bordeaux & first assembly of elements at Poitiers, France, a) Design working, b) Woodworking at Bordeaux, c)UHPC in making, d)Team work and discussion, e) Module Testing and assembly, f) Design simulation studies , [22], Author.

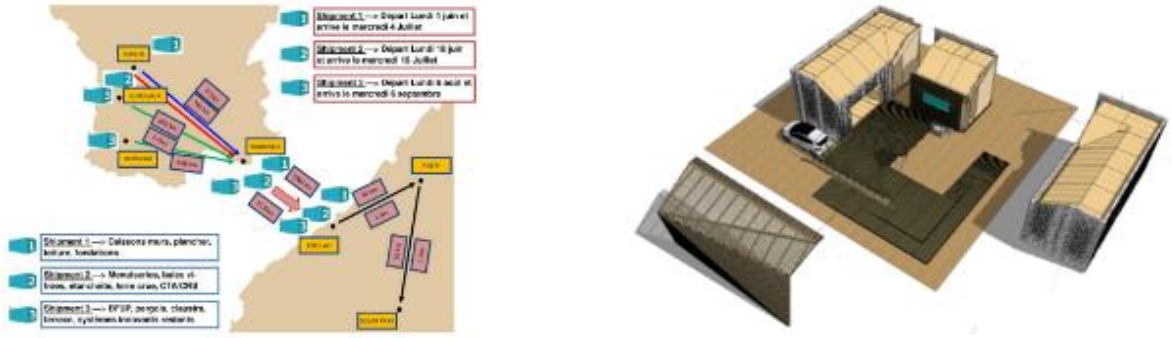


(a) (b) (c) (d)

(e) (f) (g) (h)

Figure 12: The first assembly of the BaityKool prototype at Amity University Dubai between July and October 2018, Figure 12: a) to e) are the stages of BK assembly: the pre-competition stage, a)Floor plates assembly, b)floor and core wall assembly, c)structural CLT core assembly, d) thermal insulation, e) Weather Shield assembly, Figure f) to h) shows the disassembled Modules transported to the competition site at Mohammed Bin Rashid Al Maktoum Solar Park, f)Disassembly, g)Loading on trailer, h)Transport to SDME .

Figure 12 (a) to (e) shows phases of assembly and Figure 12 (f) shows the disassembly of the prototype in three parts. Fig. 12 g) and h), shows the transport of the disassembled prototype to the Solar Decathlon Middle East 2018 competition site at the Mohammed bin Rashid Al Maktoum Solar Park in Dubai using trailer trucks. The logistic planning and strategy for assembly, disassembly, and final assembly during the competition period are shown in Fig. 13.



(a) (b)

Figure 13: The BaityKool prototype logistic planning and strategy from France to Dubai, a) Logistic planning, b)BK prototype assembly strategy, [22].

The prototype was reassembled as in Fig. 14 during the 14-day assigned duration from 31 October to 13 November 2018 at the competition site to be ready for operation to start the 14-day test period during the Competition from 14 November to 29 November 2018.



(a) (b) (c)



(d) (e) (f)

Figure 14: The BaityKool Prototype during the competition period at the Mohammed Bin Rashid Al Maktoum Solar Park in November 2018, a) BK view at SDME 2018, b) View of BK Patio, c) Vistors experiencing BK at SDME, d) West entry view, e) Electric car parking at BK, f) BK Team meet, [22].

The prototype gave positive results during the 14-day testing phase of the SDME 2018 competition. Won the overall 3rd place and for the contest first place in Sustainability, 1st place in Energy Efficiency, Building-Integrated Photovoltaics, 2nd Place for Architecture, 3rd place for Innovation, Energy management, Engineering, and construction during the completion period of 14 days in November 2018 with the team receiving the award as in the Fig. 15 [23].



(a) (b)

Figure 15: The SDME 2018 competition results of Baitykool for the overall project and the contest BaityKool results at SDME 2018, (b) BK Team receiving the AWARD, [23].

The SDME 2018 jury report, published on the BaityKool prototype's performance during the competition, provided a positive comment on the Bioclimatic performance contests. The '*Sustainability*' jury took a comprehensive approach using the nine features of the competition guidelines along with the addition of the socio-economic pillar of sustainability. The jury enumerated on the team's effort to put together comprehensive life cycle assessment to assess each aspect of the house. The use of dual functionalities in many aspects in the house such as window shading, power generation, BIPV cladding, aquarium along with the strategy of using waste water recycling was appreciated. A special mention was on the innovative approach of storing the night time cool energy during the day integrated with the thermal storage system of the house and the use of sustainable materials. For the 'Architecture' contest the jury mentioned the clarity in the concept with courtyard and driven by high performance design in the Middle-East context. The

design of the house with integrated passive strategy in all the spaces was tested thermally comfortable. The courtyard at the center of the house was mentioned as the most thermally comfortable space extending its comfort to the two main rooms the east oriented living and west oriented bedroom. There was a special mention on the use of technology integrated in the material and devices with high level of craft to the details with the well-conceived spatial arrangements making the house an ideal place living. The placement of the door and windows with its flexible operations helps with the consistent connect between the spaces and functions. The 'Energy Efficiency' contest gave special mention to the incorporation of thermal storage in to the walls and radiative sky cooling at night. The use of porous fabric for walls and ceiling acting as a diffuser, aquaponics with the fish tank and vegetation acting as a window. The automated building elements for natural ventilation, the high performance wall system with the ventilated façade and reflective elements. The 'BIPV' jury contest report had a special mention for the integration of PV with the building system with aesthetics. The vertical panels structured in line with the perforated UHPC panel on the façade and dynamic movable solar pergola canopy for the patio (courtyard). The 'Interior Design' jury commented on the multifunctional spaces with cooling system from natural resources. The 'Creative Solution' received jury special mention for the innovative implementation of vertical garden using closed water ecosystem and PV integrated system with Solar canopy and wall BIPV. The 'Engineering and Construction' mentioned excellent implementation of integrated approach between architecture and passive strategies resulting in lowest installed capacity of air conditioning system with lowest potential energy use. Potential use of radiant comfort temperature throughout the surfaces of interior and courtyard. The house got a special mention for the potential to explore better controls with integration of natural ventilation. The evaluated results and showcased homes offer an opportunity for people, professionals, and students to learn more about innovative methods [23], [24].

This innovative BaityKool prototype has been relocated from the SDME competition site to Sustainable City Dubai, where it operates as a Living Lab (BK Lab). Experiments conducted at the BK Lab to analyze field measurements and tested the effectiveness of bioclimatic strategies, solar shading, and natural night ventilation in achieving thermal comfort and optimized energy usage for cooling [19]. The experiments also assessed the architecture's form, solar canopy shading, and participation in night ventilation. Additionally, they explored the benefits of the compact envelope system, featuring Ultra High Performance Concrete walls and sun control.

General Introduction

My involvement in the BaityKool competition began at the inception stage in 2016, extended through the competition phase in 2018, and continued into the post-competition research and development stage as a team member involved in the design process, assembly at Amity University campus Dubai, and the SDME 2018 competition site. I also conducted research during the post-competition stage at the Mohammed Bin Rashid Solar Park in Dubai from 2019 to 2021, followed by relocating the prototype to a new location at the Sustainable City in Dubai. There, the platform 'BK-Lab' has extended its life as a Living Lab. Involvement in this project since the inception has sparked a research interest in the potential of bioclimatic architecture for Dubai's extremely warm climate. This study examines the thermal comfort conditions of the testing prototype to assess innovative strategies across the region's diverse seasons and climate conditions.

Research needs and Subject positioning

Since the urban population spends most of its time indoors, creating a comfortable thermal environment is essential. Thermal comfort in the quickly growing, modern, and urbanized Middle East relies heavily on air conditioning, which consumes significant electricity and natural resources. A major concern is how buildings disconnect inhabitants from nature and their surroundings. The UAE government aims to develop a diverse economy rooted in sustainable principles, promoting sustainable development for new projects. The 21st century has seen efforts in the Middle East to adopt a hybrid approach that balances shading, natural ventilation, and insulation with modern technology to create efficient cooling systems and maintain good thermal comfort throughout the year. The BaityKool platform employs an architectural strategy inspired by traditional courtyard houses to evaluate building performance, using passive and active environmental control methods. These responses are based on the building's orientation across various climatic conditions. The benefits of the central shaded courtyard system were analyzed through heat control measures, including solar shading with roller blinds made of different materials placed inside and outside the openings (windows and doors). Night ventilation offers advantages like utilizing cooler nighttime temperatures, removing heat through cross ventilation, and naturally cooling indoor spaces via east- and west-facing windows and ventilators in the central courtyard featuring the aquaponics system. The strategy of opening and closing windows and applying passive and semi-passive solutions was tested during different times of day, seasons, and weather conditions.

The physical factors affecting thermal comfort, such as air temperature, mean radiant temperature, relative humidity, and air velocity, were analyzed using assessment models for bioclimatic comfort by Givoni [3] and for the energy reduction potential achieved with solar shading and night ventilation strategies. The thermal comfort conditions of occupants were evaluated to assess the performance of the passive and active strategies implemented in the design, based on bioclimatic architecture. Experiments were conducted at various times of the day, night, and throughout different seasons. The study also examined the energy usage patterns during these periods, both with and without occupancy, during the experiment. The goal was to understand potential energy savings from reducing the load on the air conditioning system while maintaining thermal comfort in accordance with ASHRAE Standard 55-2017 [25].

Research problematic

As temperatures rise and energy consumption increases in the UAE, there is an urgent need to design buildings that ensure thermal comfort without relying heavily on mechanical systems. Modern buildings often ignore passive strategies rooted in regional knowledge, resulting in energy-inefficient structures. Global comfort standards and urban expansion require high-performance envelopes that can support dense, vertical development. Traditional architecture once provided climate-responsive solutions, but it has largely been replaced by Western models that are less compatible with the local environment. This disconnect raises questions about how bioclimatic principles can be reintroduced into modern construction. The research aims to assess the effectiveness of these strategies in extreme climates through experimental testing. The BaityKool prototype acts as a case study to evaluate and refine these design approaches.

Research Question

- How effective are passive strategies such as solar shading and natural ventilation in enhancing thermal comfort in very hot climates?
- In what ways can traditional architectural principles be integrated into modern high-performance buildings in the UAE?
- What role does the building envelope play in reducing energy consumption and maintaining indoor comfort across seasons?

- How can findings from experimental living labs inform future regulations and design standards for bioclimatic architecture in arid regions?

Objectives:

- To analyze and test the potential of bioclimatic design for buildings in Dubai's extreme warm climate, testing the BaityKool prototype designed with these strategies for thermal comfort, which include solar shading and night ventilation.
- Test the bioclimatic strategies on the BaityKool prototype to evaluate the thermal comfort provided by solar shading and night ventilation.
- To assess how patio (courtyard) design influences thermal comfort in residential buildings located in extremely warm climates by analyzing its impact on temperature regulation.
- Assess the significance of proper, smart management of the building's operation based on seasons and comfort requirements.
- To verify through field experiments and validate the real-time performance of the recommended strategies.

Scope of research

The research focuses on the self-sustaining, eco-responsive, bioclimatic prototype designed, built, and tested at the SDME 2018 competition. The prototype tested for the fourteen-day competition period in November 2014 won seven awards for the contest and overall third place. The bioclimatic intelligent architecture installed at The Sustainable City Dubai, UAE, is a living laboratory for research and development. The field, which is located in the arid desert climate of Dubai, enables testing of the prototype for its design and performance in the extremely warm climate. Experiments conducted for testing energy balance with reduced energy demand for cooling under various scenarios of solar shading and night ventilation across the year.

Thesis structure

The chapter is divided into five parts, highlighting the need for climate-responsive architecture in extremely warm climates. It explains the design and construction of the BaityKool prototype as Bioclimatic architecture for Dubai's very hot climate. The prototype served as a tool to test thermal

comfort achieved through solar shading, natural ventilation, and night ventilation. The setup and plan are detailed. The analysis and results, along with discussion and conclusions, explore the potential of design strategies for Dubai's extremely warm climate.

Chapter 1

This chapter examines the theoretical background and scientific method, exploring the definitions, parameters, and factors based on literature studies. It discusses the climate in Dubai, UAE, where the BaityKool Living Lab is located, to evaluate climatic conditions across two seasons and two transitional periods in the year. The architecture in the UAE is analyzed, along with factors influencing climate-responsive design based on vernacular, modern, and contemporary building practices. Energy use in buildings is assessed through residential building typologies to understand energy patterns and demand across seasons and transitional periods. Passive strategies, such as solar shading and night ventilation, are explained with experimental models, parameters, equations, and relationships, which lead to the development of experimental protocols.

Chapter 2

Explains BaityKool Living Lab as a tool for the experimentation of bioclimatic architecture in extreme warm climates. The architectural design concepts, bio-climatic design strategies, the envelop design, structure, composition, natural lighting, ventilation design, and green core patio (courtyard) are explained. Details are expressed for the building operation for solar shading systems and natural ventilation to improve thermal comfort conditions and minimize energy consumption. The study of the climate characteristics of the study site in the context of the BaityKool prototype is described.

Chapter 3

The experimental spaces, their characteristics, the setup for solar shading, natural ventilation, and patio shading, along with the experimental scenarios, protocols, data acquisition tools, and measures with specified precision levels, are explained. The research methodology for the solar shading and night ventilation scenarios justifies the purpose of the experiments, their scenarios, and measures, with an analysis planned and measurement parameters for data collection. The

research activities are organized to understand the relationship between thermal comfort parameters and energy usage patterns across different seasons.

Chapter 4

This chapter evaluates passive strategies for thermal comfort in the BaityKool prototype, tested under extreme climate conditions. Results demonstrate that solar shading and natural ventilation significantly reduce indoor temperatures, with shading devices decreasing heat gain by up to 8°C. Translucent envelope materials and cross-ventilation maintained comfortable indoor conditions despite wide outdoor temperature fluctuations. Vegetation and architectural features improved visual comfort and minimized solar radiation. The building envelope stabilized indoor temperatures with minimal variation. The findings support integrating passive and active strategies in bioclimatic architecture to achieve energy-efficient performance in hot climates.

Chapter 5

Discussion and conclusion on the data results, their implications, and evidence of findings for creating a framework for the intelligent management of building operations based on changing seasons and comfort needs for an annual energy balance. The summary of findings for the tested hypothesis would benefit architects and construction professionals in adopting strategies for improved thermal comfort and energy efficiency in buildings located in extreme warm climates.

Chapter 1:

Exploring bioclimatic approaches for thermal comfort in extreme warm climate: a literature review

Chapter 1: Exploring bioclimatic approaches for thermal comfort in extreme warm climate: a literature review

Chapter 1 explores the bioclimatic relationship between climate, building design and techniques, and occupants' control systems. The potential of bioclimatic architecture was analyzed for an extreme warm climate, considering factors that promote thermal comfort indoors to identify the need for an eco-responsive solution with energy savings, especially in the Arabian Peninsula region. The study is divided into four parts covering the following topics:

- Bioclimatic concepts, strategies, and tools to analyze strategies for application in design.
- Climate study for an extreme warm region
- Thermal comfort factors indoors in buildings
- Architecture of the past and present in the Arabian Peninsula region

1. 1 Bioclimatic principle, strategies, evolution, and design tools

This session reviews the literature on bioclimatic principles to explore strategies that could potentially reduce energy use in extremely warm climates. The development of these practices is discussed up to the present, with a focus on their application, benefits, and limitations. An investigation into models that analyze techniques for evaluating designed and constructed projects based on bioclimatic principles for hot climates is also proposed.

1.1.1 Bioclimatic Concepts

Bioclimatic architecture involves adapting a dwelling to its climate using advanced technology and being sensitive to the natural environment. Bioclimatic adjustments are made in three directions: energy, human health, wellbeing, and sustainability. These are achieved by considering the climate particularities of the building location to develop strategies for comfortable conditions in buildings [26], [27]. A bioclimatic approach is a way of designing buildings in harmony with the climate, the local environment, and the occupant's comfort condition. It intrinsically encourages the use of environmental resources and the minimization of energy consumption, thus promoting sustainability [28]. It relates to the deep-rooted relationship between humanity and nature, prioritizing natural elements such as sunlight, wind, and vegetation to improve thermal

comfort conditions and minimize environmental impacts. Bioclimatic principles offer a holistic approach to designing buildings that respond to climate change [26]. The bioclimatic design understands the complexity and sensitivity of the local natural environment, adapting to it with the support of innovative, advanced technologies integrated into the ecosystem [29]. The bioclimatic concept must consider various levels of climate, ranging from the macro to the micro level, to achieve thermal comfort by interacting energetically with the exterior environment [26]. Vernacular architecture has been influenced by the promotion of using available resources and low-tech technologies, customizing the design to meet the functional needs and cultural preferences of its inhabitants. Knowledge transfer in vernacular architecture was passed from one generation to another. Until early modern architecture, bioclimatic design was a part of the practical knowledge of indigenous buildings throughout history [30]. By the 1950s, with the widespread availability of air conditioning systems, bioclimatic design became less evident in practice, literature, and built works. The emergence of global environmental concerns in the 1990s underscored the importance of energy conservation, with a cascading effect that reduced pollution and helped mitigate global warming. This led to the inclusion of landscape, water, and waste nutrient recovery [31], [32]. An early definition of bioclimatic design emphasizes the overlapping of biology, climatology, and architecture. The development of Passive Low Energy Architecture (PLEA) has reframed Bioclimatic design in the context of sustainability [33].

The complex relationship between climate extremes and human comfort demands a redefined form and fabric for the building. Bioclimatic architecture has evolved from the earlier overlap between the fields of architecture, biology, and climatology, drawing inspiration from the fundamentals of vernacular architecture. It has followed a natural evolutionary process, driven by factors such as resources, environmental concerns, and the interplay of novel design concepts, building sciences, building standards, codes, construction technology, and cost [26]. With scientific tools and simulation-based optimization methods, the building design and thinking process are enhanced, leading to improved performance for human comfort conditions [34]. Climate change and its effects present additional challenges and requirements for developing a sustainable built environment with Eco-adaptive architecture [35]. Following bioclimatic architecture helps in achieving an optimal human comfort without complete dependence on mechanical systems. Bioclimatic architecture is now treated as a critical concept for achieving sustainability [36].

Though sustainable design awareness is growing worldwide, the designs are rarely based on Bioclimatic concepts, as the broader aspect of design is oriented toward energy certification [29].

1.1.2 Evolution of Bioclimatic Architecture

Advanced techniques and design methods, combined with controls on building performance, have been achieved through simulation-based design for buildings using innovative technologies, resulting in high-performance, green, and zero-energy buildings [37]. The simulation-based optimization method, which incorporates varied environmental criteria, helps save 10% to 30% of energy consumption in buildings with passive solutions [27]. The Bioclimatic approach has been evolving since the late 19th and early 20th centuries up to the present time, as *Bio-inspired architecture* and *technologies,* with fundamentals based on vernacular architecture inspired by nature and adapted to the local environment and its conditions [36]. By the early 20th century, it had evolved into *Organic architecture,* guided by the philosophy of creating harmony between human habitation and nature while reducing the need for energy and resource consumption. The mid-20th century witnessed the emergence of the architectural trend of *bioclimatic architecture, which incorporated passive design solutions that enabled buildings to adapt to climatic conditions, thereby creating an indoor environment that met the needs and demands of occupants* [27]. The concern of building energy issues led to the redefinition of Bioclimatic architecture, with the term "synergy". This integrates advanced design techniques and mechanical systems with passive solutions. The holistic approach enhances energy efficiency and comfort, paving the way to "zero-energy" buildings by the end of 20th Century bioclimatic architecture has evolved as *Green buildings* with a genuine co-operation developed between the architecture and its natural environment; Green Buildings aim to produce eco-friendly, resource-efficient buildings having low environmental impact analyzed using building's life-cycle. This created an interrelationship between the green building and the microclimate, the natural environment, maintaining good indoor comfort conditions for the occupant, and technological systems and architectural design [38]. The recent evolution is the *Eco-adaptive approach,* with the importance of architecture to be eco-friendly, adaptive to the changing climate, and resilient to natural disasters. Designs are thought to incorporate technology into the operation systems of buildings, utilizing innovative technologies to gather data, optimize functions through automated adjustments, and ensure the buildings can function in the event of technology failure during any disaster [39]. Thus, the eco-

adaptive move works with sustainability, balancing the environment. The sustainable design that achieves the most with the least, as demonstrated by M.I.S.T., incorporates passive architecture and designs higher-quality, efficient projects with longevity that align with the context through passive strategies [11]. Table 1 shows the evolution of biolimatism.

Table 1: The architectural evolution towards and from bioclimatism [27]

Architectural trend/period	**Adaptation features of architecture**	**Time**
Prehistoric architecture	Architecture with the simplest forms of climatic adaptation, e.g., use of locally available material to build shelters or caves to avoid predators/bad weather.	Prehistoric age
Vernacular architecture	Adaptations in architecture to local natural and social conditions.	Evolved throughout history
Bio-inspired architecture and technologies	Culminating in an organic style inspired by nature, adapting to local environments and conditions.	From the late 19th and early 20th centuries up to the present time
Organic architecture	A philosophy of architecture promoting harmony between human habitation and the natural world, reducing the need to use energy and resources.	Frank Lloyd Wright (1867–1959), one of the four most influential architects of the 20th century, coined the term organic architecture.
Bioclimatic architecture	***Passive design solutions adapt to climatic conditions, creating indoor comfort that satisfies the demands of building occupants.***	***Since mid-20th century***
Passive and low-energy architecture	Employing advanced design techniques to build more energy-efficient and more comfortable buildings. The trend has partly evolved towards creating zero-energy buildings.	Since 1980s
Green buildings	Buildings that are respectful of their natural environment and strictly control their environmental impacts throughout their entire lifecycle while maintaining good indoor comfort for occupants are ideal.	Since the end of the 20th century
Sustainable architecture	Meeting the needs of present generations without compromising the ability of future generations to meet their needs, while balancing environmental, social, and economic issues in the building design.	The future

The bioclimatic approach takes considers three steps:

(i) The definition of the measure and requirements for human comfort is from a study in biology.

(ii) The review of the climatic conditions from the climatology study.

(iii) A rationality in the architectural solution, from the involvement of engineering sciences.

The designs created in the built environment that adapt to bioclimatic conditions require environmental analysis based on the location for each specific time of day to understand the changes in the dynamic ecosystem, with the analysis reapplied and monitored [29].

1.1.3 Benefits of Bioclimatic Architecture

Bioclimatic architecture promotes a holistic design approach that fosters balanced biodiversity, integrating infrastructure in harmony with the existing ecosystem to achieve equilibrium and promote biodiversity [40], [29]. Bioclimatic architecture adapts the dwelling to the region's climate, utilizing advanced technology that is sensitive to the natural environment. The Bioclimatic adjustments comprise three directions: energy, human health and wellbeing, and sustainability, achieved by considering the climate levels of the building location to develop strategies for comfortable conditions in buildings [27]. This process, evaporative cooling, transforms water into vapor, resulting in a documented temperature decrease of 5°C. This effect has been observed in the carefully designed green spaces of the Al Barari community in Dubai, UAE. This eco-friendly development, which combines residential, commercial, and recreational areas, has effectively created a microclimate. The mix of dense plant life and strategically placed water features helps reduce solar radiation reflection, leading to naturally and sustainably cooler air [41], [42]. The developments can be self-sustaining, energy-efficient, and less energy-reliant through the use of passive and active strategies, thereby reducing the loads on cooling and lighting systems. An increased efficiency can be achieved by incorporating sustainability and energy conservation parameters through passive strategy in the sustainable off-site modular construction ‘Zero-Energy Houses’. These are developed for the hot-arid climate, as discussed in case studies for houses in the desert environment [19]. The integration of renewable energy in buildings have environmental benefits and is crucial in addressing the rising energy demand and mitigating global warming with the green buildings. The incorporation of renewable energy systems with innovative building

design and layouts, artificial intelligence technologies would be effective in optimization and being eco-friendly [43].

1.1.4 Bioclimatic strategies for extreme warm climate

The UAE climate influences the choice of bioclimatic strategies based on macro and microclimate conditions. The building envelope is essential for resisting solar heat gain and maintaining comfortable indoor temperatures [23]. For very hot climates, bioclimatic design can utilize a 'Cool Degree Days' approach, classifying local climate conditions with passive architectural strategies [31]. A study on thermal behavior in UAE residential buildings found that the size and orientation of glazing can significantly reduce energy consumption; limiting glazing to two elevations can cut total annual energy use by 55%, with glazing covering only 10-20% of these surfaces. Buildings with perimeters ranging from 80m to 115m and a window-to-wall ratio of 1:6 performed better overall. The study recommends minimizing glazing, using shaded windows, and designing longer east and west elevations. Shading devices on windows, walls, and roofs, along with night ventilation, enhance thermal performance. North-south orientations show better thermal behavior. Courtyards help improve indoor conditions by shading walls and creating a more pleasant environment, while vegetation such as dense shrubs and vines helps lower air temperatures through evaporative cooling—using wet floors, spray-painted walls, and water fountains. Multiple hypotheses confirm that vegetation combined with water bodies enhances outdoor cooling, which in turn improves indoor thermal conditions by trapping cool air [44].

The strategies to be set are:

- Minimize heat transfer (Conduction): This strategy is effective when outdoor temperature significantly differs, either lower or higher, from the indoor comfort ranges. This is achieved with "insulation", which is to be considered in summers when the ambient temperature is within or above the comfort range (between 22 °C and 28 °C mostly depends on the age of the individual, gender, type of the building and mode of ventilation) and when comfort cannot be achieved with natural cooling strategies [45], [25].
- Daily periodic heat flow: Using earth-sheltering and berming methods takes advantage of the high thermal inertia of underground materials, creating a noticeable delay in heat transfer. This delay helps improve indoor thermal comfort and decreases the need for mechanical cooling. These passive design practices work especially well in hot, dry

climates with large temperature swings between day and night. For example, the time lag in a masonry wall can delay the day's thermal comfort until evening [38], [46], [47].

- Minimize air infiltration: This refers to uncontrolled air leakages around windows and doors, through cracks, joints, and faulty seals in the building envelope system. Air infiltration and the resultant exfiltration of cooled or heated air are the most intractable sources of energy loss in buildings [48]. Hassouneh et al [49] studied how uncontrolled air leakages, such as those around windows and doors, can significantly impact a building's heating and cooling energy use in Amman city. They concluded that choosing glass type A (made from borosilicate glass) and glass type B (soda-lime glass) is preferable to save energy, considering the influence of infiltration.
- Provide Thermal Storage: The thermal mass in the insulated envelope is essential for reducing fluctuations in air temperature. It absorbs heat during winter and functions as a heat sink in summer [33], [31]. Zhang et al. [50] emphasize the role of thermal mass, both conventional and latent, as a passive mechanism to buffer temperature fluctuations by absorbing heat during the day (acting as a heat sink in summer) and releasing it during cooler periods (storing heat in winter). Bouzouidja et al. [51] investigated the indoor thermal performance of the Bioclimatic house built for extreme warm climates, specifically in Dubai. They evaluated the thermal performance of clay mixed with sawdust (3%, 5%, 10%) for sustainable building envelopes in hot climates. This study aims to improve insulation using low-carbon, bio-based materials.
- Windbreaks can minimize the impact of wind on comfort. Mohammadi et al. [52] conducted a computational fluid dynamics (CFD) study to show how vegetation-based windbreaks integrated in buildings (sky gardens) can reduce wind speed and improve thermal comfort. They observed that the vegetation as a windbreak solution significantly reduces wind speed (reduction of 10%).
- Promote ventilation: Use the natural cooling process with two processes, "Cross-ventilation" and "stack-effect ventilation" [46].
- Promote mechanical ventilation powered by renewable energy: A fan powered by a renewable energy source can be used to cool indoors when there is insufficient wind or when the stack pressure is different. [5] .

- Minimize solar heat gain: Minimize the effect of direct sun by shading the opening facing the exterior. Use radiant barriers to minimize the exposure of building surfaces to the sun [38]. Freewan [53] Conducted a study on the effect of shading devices (e.g., vertical and horizontal fins) on indoor air temperature at Jordan University of Science and Technology, Jordan (hot and dry summers). The results confirm that adding vertical or horizontal fins can reduce air temperature by up to 2°C during summertime (1pm to 4pm).
- Promote Radiant Cooling: Zhao et al. [54] in this review, explore how heat loss from building exteriors occurs when their surface mean temperature exceeds that of the night sky, especially considering surface emissivity, atmospheric windows, and solar irradiance. Hu et al. [55] explored the influence of a hybrid panel that absorbs heat during the day and radiatively cools at night. They found that nighttime surface temperatures were 1–6°C below ambient, enabling passive cooling under real-world conditions. Aketouane et al. [56] tested a water-based radiative cooling system across three nights in Dubai with ambient temperatures between 22.7 and 31.4 °C. The study demonstrates that a nocturnal radiative cooling system can consistently cool surfaces below ambient temperature, approximately 3°C, and sustain around 30-45 W/m^2 of cooling power in real-world, hot-weather conditions.
- Promote evaporative cooling: Evaporating moisture in the incoming air stream can create sensible cooling. It could be done by spraying water on the exterior envelope and roof. The technique is helpful for hot-dry climates. Mechanically done by economizer-cycle-evaporative cooling, done with air conditioning [46], [5].

1.2 Climate study for an extreme warm region

The bioclimatic architecture aligns the dwelling with the climate. To achieve a holistic approach, understanding the UAE climate at the macro and micro levels is essential for an in-depth environmental analysis and determining the design strategies concerning the local context.

1.2.1 Understanding Climatic Factors at a Global Level and the Extent of the Extreme Warm Climatic Region.

Regional climate significantly influences architectural design strategies aimed at achieving optimal human comfort conditions [38]. Climate and its changing nature strongly influence bioclimatic design strategies in the built environment.

As per Köppen climate classification as in figure 16, shows 5 main climate groups divided as per the seasonal precipitation and the temperature pattern of the region - Tropical Climate, Dry Climate, Temperate climate, Continental climate and Polar Climate.

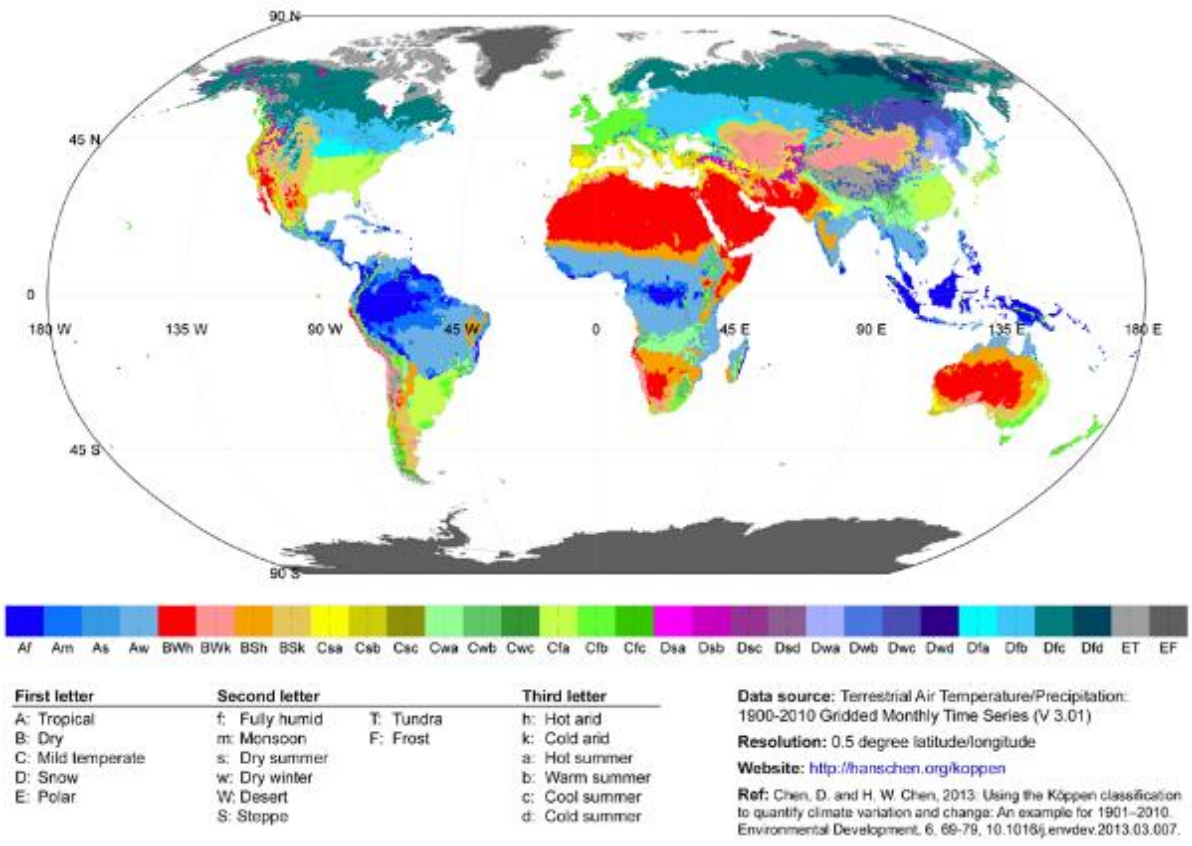


Figure 16: World map of Köppen climate classification for 1901-2010 based on Chen and Chen [57]

The climate of the UAE is classified as hot desert climate (BWh) under the Köppen-Geiger climate classification system (Fig. 16) [58]. This classification is characterized by extremely hot summers, with daytime temperatures often exceeding 45 °C. Mild winters, where average temperatures range between 14 °C and 24 °C. Very low annual precipitation, typically less than 100 mm, mostly falling between November and March. High solar radiation and low relative humidity, although coastal areas like Dubai and Abu Dhabi can experience higher humidity due to proximity to the Persian Gulf [59]. The UAE's climate is influenced by its subtropical desert location, with minimal

cloud cover and intense solar exposure throughout the year. These conditions contribute to high evaporation rates, making water scarcity a critical issue.

Recent high-resolution Köppen-Geiger climate classification maps confirm the persistence of the BWh classification across the UAE, both in historical (1980–2016) and projected future scenarios (2071–2100), indicating the region will remain arid under climate change projections [58]. More than 80% of the world population lives in warm-hot climates, and a million people live in extreme hot climates. The "international" model of architecture as practiced in the region takes little effort on the principles of low energy consumption by buildings and comfort conditions reliant on technical equipment like air conditioners, consuming a high energy level. In regions with hot climates, air conditioning is generally the only solution to ensure thermal comfort. However, this practice leads to an increase in electricity consumption. In the UAE, for example, it is estimated that 60 to 70% of electrical consumption is dedicated to this [60]. Kharrufa and Makky [61] tested an evaporative system to cool the envelope of room in Ajman University campus, UAE during 2018. They compared two model buildings: one with a cooled secondary envelope (via evaporative cooling), and one with standard insulation per Dubai standard. They observed that passive secondary envelopes achieved 40 to 47% electricity savings, and evaporative cooled envelopes achieved 52–54% savings compared to the baseline insulation. Significant simulation results on passive cooling strategy in the hot and arid region showed 26% reduced consumption in the annual energy when compared to the real energy bill for a set of residential buildings analyzed in the UAE [41]. Climate has become one of the key factors in developing solutions and strategies for bioclimatic architecture with an eco-adaptive character [62]. There is a need to develop specific design strategies suited to the local climatic conditions of the warm desert climate to maximize human comfort and reduce energy use in buildings. There is a need to understand the climatic conditions, seasonal patterns, and variance in temperature and humidity between day and night to analyze the results of the Bioclimatic strategies developed in the UAE.

1.2.2 Summary of climate study in Dubai, UAE

The weather data from the National Center of Meteorology, Ministry of Presidential Affairs, Climatic report 2012-2024 (Appendix A) shows consolidated details as in Table 2. Seven months of the year, from April to October, with a mean temperature above 26 °C. Humidity exceeds 50% for 11 months of the year, with low annual precipitation, wind speeds ranging from fresh breeze

to strong breeze (21.5 – 25.8 km/h), and high solar radiation, peaking at 4210 in January and December to 7409 in June.

Dubai experiences a prolonged period of excessively high temperatures, with daytime extremes in summer reaching 40-50°C, nighttime lows of 30-35°C, limited natural ventilation, and high humidity of 60-90%. The long summer season, with intense solar radiation and moisture from May to October, creates a complex living environment. The climate seasons are determined based on Dubai's mean temperature and humidity, as shown in the Table. 2 with the Peak summer months May to September, Winter months January, February, November, December, and short transitional months February-March and October-November.

Table 2: Weather Data at Station: DWC Al Maktoum I.A, Dubai, for the period from 2012 to 2024

Month	Temperature (°C)			Humidity (%)			Rainfall (mm)	Wind (km/h)		Solar Radiation (W/m2)
	Max	Mean	Min	Mean Max	Mean	Mean Min		Mean	Max	
Jan	31.3	19	5.6	85	65	39	16.2	13	63	4264
Feb	36	20.3	6.5	85	63	35	11.4	14	63	4981
Mar	40.7	23.4	9.4	82	57	29	16.7	15	67	5790
Apr	44.5	27.6	14.8	73	48	21	16.9	15	56	6680
May	47.1	31.5	16.9	70	44	18	3.9	16	69	7276
Jun	49	34.2	21.9	74	48	19	0.3	16	52	7409
Jul	49.5	36.2	24.6	70	47	22	0.0	16	63	6808
Aug	48.5	36	24.4	69	46	21	0.0	15	56	6598
Sept	46.9	33.4	21.2	78	52	21	0.0	14	50	6362
Oct	42.4	29.7	15.8	81	57	25	0.6	13	44	5490
Nov	37.2	25	11.8	82	60	32	7.0	13	61	4554
Dec	33.2	20.9	8.4	84	64	37	1.4	12	46	4210

The Climate Season classification for Dubai according to Yusta-Garcia et al. includes maximum and minimum temperature and humidity values, as recorded in the climate data from 2005. The

climate seasons are classified from S1 to S6, as illustrated in Fig. 17. This classification indicates the comfort zone with a temperature range of 19-26°C, the passive hot zone with temperatures above 26 °C, and the cold zone with temperatures below 19 °C.

- *Climatic Season S1: cold days and cold nights.*
- *Climatic Season S2: cool days and cold nights.*
- *Climatic Season S3: temperate days and nights.*
- *Climatic Season S4: hot days and cold nights.*
- *Climatic Season S5: hot days and warm nights.*
- *Climatic Season S6: hot days and hot nights.*

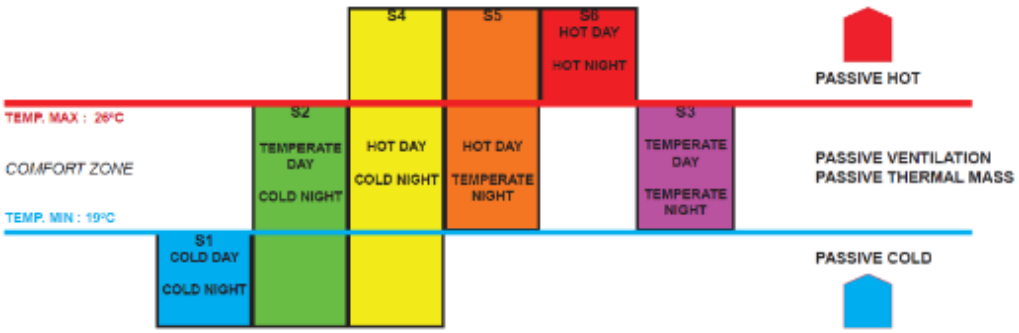


Figure 17: Diagram of 'Climatic Seasons' with examples of cities and their seasons, [62]

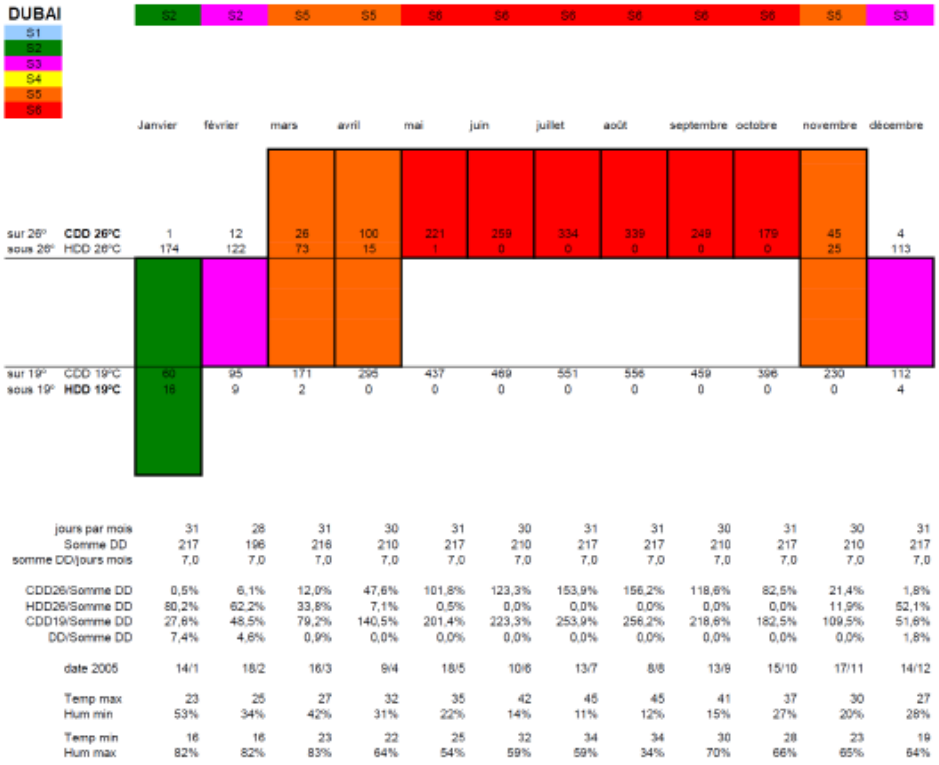


Figure 18: Comparison of Climatic Seasons method with the temperature-humidity values of 2005 for Dubai, [62].

The climate data analysis shows the climate season with high temperatures from May to October, labeled as S6, low temperatures from January to February, labeled as S2, and low temperatures in March, April, and November, labeled as S5. Fig. 18 illustrates the climate season for Dubai, including the CDD and HDD, along with the values for Temperature Max, Relative Humidity Min, and Temperature Min & Relative Humidity Max [62].

Figure 19 provides a graphical representation of the seasons identified for the experimentation of the BK prototype in Dubai, aligning with the climate season classification for Dubai, as indicated in the Cooling Degree Days analysis in Figure 18 [62].



Figure 19: Climate Season classification for the experimentation at the BK prototype, Dubai

The climate in the UAE is warming up by 0.4°C, as seen in the long-term average report (2003-2022), with an annual mean temperature of 28.4°C, which is ranked as the fifth warmest year on record. January's lowest monthly mean temperature of 19.1°C is 0.9°C above the long-term average (2003-2022). Climate change effects are observed in an alarming situation, necessitating resilience, adaptation, and the application of bioclimatic and sustainable design concepts to mitigate climate change [63]. The Climatic Season in Dubai, characterized by cool days and cold nights in January, and temperate days and nights in February and December, presents an opportunity to utilize passive strategies for achieving thermal comfort while saving energy and reducing the need for air conditioning. The weather data helps develop appropriate design strategies for the extreme warm climatic conditions, taking advantage of the desirable climate in building design, construction, and operational phases. *The architecture design and construction practices must embrace the core principle of 'design for climate', specifically the bioclimatic architecture suited for extremely warm climates.*

1.3 Thermal Comfort in Buildings

Human health and comfort are considered important factors in evaluating indoor environments. Comfort refers to an optimal thermal condition with minimal effort needed to maintain the body's thermal balance [22]. The interpretation of user health and productivity is linked to heat and airflow within spaces. Maintaining the balance of heat flow from the human skin to the environment is a fundamental physiological principle that keeps us alive. Humans respond by adjusting external and internal factors, resulting in a body temperature change of 1 to 2°C. Metabolic heat production depends on clothing, activity level, and active heating and cooling devices used to protect core temperature and ensure thermal comfort.

1.3.1 The factors that affect thermal comfort:

a) Environmental – Represented graphically as in figure 21, this affects heat dissipation from the body to the environment through external variables such as :

- Air temperature – The most essential factor measured by dry bulb temperature (DBT)
- Air movement—Measured by its velocity (v, m/s), air movement also affects the evaporation of moisture from skin, creating an evaporative cooling effect.
- Humidity – Expressed as relative humidity (RH, %). Humidity in the air affects evaporation rate, absolute humidity (AH, g/kg), and vapor pressure (p, kPa).

- Radiation – This exchange depends on the average temperature of the surrounding surfaces. Referred to as Mean Radiant Temperature (MRT), it is approximated by Globe Temperature (GT), which is measured using a matte black copper sphere that responds to the net radiation from the surroundings. When GT > DBT, it indicates radiation is received; when GT < DBT, it indicates the surrounding surfaces are cooler than the air, and radiation is emitted. In still air, MRT equals GT.

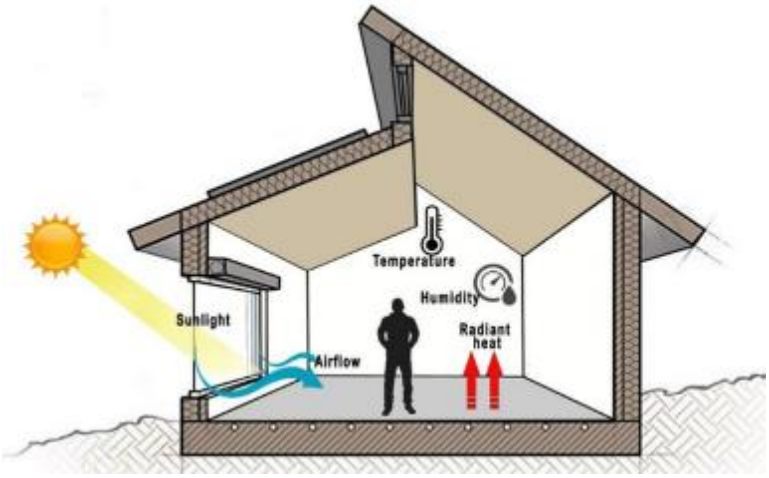


Figure 20: Representation of environmental factors for thermal comfort [64]

b) Psychological Factor

The human body produces heat continuously with two kinds of metabolic heat production:

- Basal metabolism caused due to continuous biological process
- Muscular metabolism caused due to activities

The speed and amount of heat transfer from the human body to the environment by conduction, convection, and radiation are factors in the thermal comfort level. Figure 23 explains the body temperature in condition 'A' with cool ambient temperature in the environment, the core area preserved as 37°C contracts, and the shell area expands. Condition 'B' is a warm ambient temperature in the atmosphere, and the body is preserved at 37°C and expands. The yellow areas in 'A', 'B' and 'C' indicate the "acral" regions that help control the body temperature by constricting blood vessels with a fall in body temperature. Arteriovenous anastomoses (AVA) present in the acral region open and close to allow or prevent rapid healing loss from the skin. The age difference and the gender of individuals affect the temperature distribution.

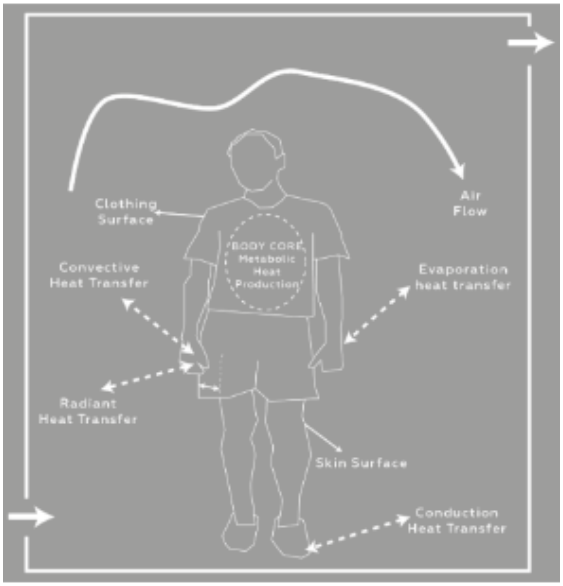


Figure 21: Heat exchange from human body to the environment, [62].

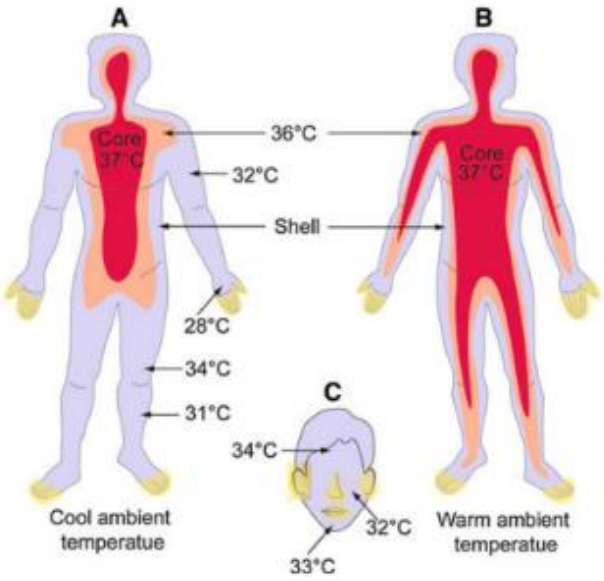


Figure 22: Human body temperature, with condition 'A', 'B' & 'C', [65].

Table 3 shows the typical metabolic rate expressed as power density, per unit body area (W/m^2). In the unit devised for thermal studies for an average person (W), 1 met = 58.2 W/m^2. For an average-sized man, this corresponds to approximately 100 W. The Metabolic Equivalent of Task developed on the fundamentals of Du Bois (1916) proposed an estimate using equation 1 for the

body surface area based on body mass (M, in kg) and height (h, in m), which is referred to as the "DuBois area" (m^2).

$$A_D = 0.202M^{0.425}h^{0.725} \qquad Eq.(1)$$

e.g. for a person of 1.7m height and 70 kg body mass

$$A_D = 0.202 \times 70^{0.425} \times 1.7^{0.725} = 1.8m^2$$

Table 3: Metabolic rates for different activities [62]

Activity	met	w/m^2	W(av)
Sleeping	0.7	40	70
Reclining, lying in bed	0.8	46	80
Seated, at rest	1.0	58	100
Very light work (shopping, cooking, light industry)	1.2	70	120
Medium light work (house, machine tool)	1.6	93	160
Steady medium work (jackhammer, social dancing)	3.0	175	300
Heavy work (sawing, planning by hand, tennis)	6.0	350	600
Very heavy work (squash, furnace work)	7.0	410	700

A comfortable indoor microclimate, which requires optimal indoor environmental conditions, entails thermal comfort, proper air humidity, a sufficient air exchange rate, and adequate oxygen content. Poorly ventilated buildings and systems enhance the risk of indoor virus transmission [66].. The indoor climate and natural lighting play a crucial role in creating a positive impact on the user's comfort [29].

1.3.2 Scientific Models and Standards to Assess Thermal Comfort Indoors:

According to ASHRAE standards 55 Thermal Environmental conditions for human occupancy, the environmental factors such as temperature, thermal radiation, humidity, and air speed, along with personal factors like activity and clothing, determine indoor thermal conditions, and individual comfort levels differ from person to person [67], the adaptive model of thermal comfort was the development to the Predicted Mean Vote model with the occupant as a passive recipient of their thermal environment assuming an ideal temperature is a fixed physiological constant. The

Adaptive Model of Thermal Comfort views occupant as an active participant, the model built on the principle that people adapt to the thermal environment in three ways as indicated below:

1. **Behavior adjustment** – Any modification made consciously or unconsciously to modify heat and mass fluxes which govern the body's thermal mass, classified by responses into
    - Personal with clothing change
    - Technological with the switching of an air conditioner
    - Cultural with having a siesta on a hot summer day
2. **Physiological** – This results from the change in exposure to thermal environmental factors, which reduces strains induced by the exposure. This can be further classified as genetic adaptation and acclimatization
3. **Psychological**—This dimension refers to perception, alterations, and reactions to sensory information, including experiences and expectations.

The occupants of the thermal environment parameters regard the heat-balance model as a partially adapted model, as it acknowledges the behavioral adjustment:

- Adaptive Model – A relation of acceptable temperature ranges or indoor design temperature to the outdoor climatological parameter in a linear regression.
- Insulation, Thermal – Sensible heat transfer provided by clothing, an intrinsic insulation from skin to clothing surface expressed in 'clo' units, the clothing level that measures the insulating ability to help a person maintain a comfortable body temperature in an environment.
- Mean monthly or daily effective outdoor temperature – 'ET' calculation of the air temperature and humidity with the meteorological measurements for 6.00 am outdoor temperature assumed minimum and 3.00 pm outdoor temperature assumed maximum for a calendar month/day
- Neutrally, thermal – the indoor temperature index value (operative temperature), the mean neutral vote on the thermal sensation scale by a sample of occupants.
- PMV, analytics—The Predicted mean vote index is analytically calculated from estimates of six comfort parameters: Mean air temperature, radiant temperature, air speed, humidity, clothing thermal insulation, and metabolic rate.
- PMV, adaptive – Optimum thermal comfort temperature, thermal neutrality corrected for

Semantics as per the outdoor climate. It predicts the operative temperature as the analytics with the mean outdoor effective temperature with the usual four inputs Clothing Level (clo), Metabolic rate (met), Relative Humidity (RH) , and Air Velocity (v).

- Sensational, thermal – a category of conscious feeling – Cold, Cool, Slightly cool, Neutral, Slightly Warm, Warm, Hot.
- Summer – defined as the cooling season
- Winter – defined as the heating season
- Temperature, optimum operative – a satisfactory temperature for several people with a given clothing and activity level.

The research by Richard De et al. [68] on developing an adaptive model for thermal comfort and preferences, based on the ASHRAE RP-884 project, reveals the differences between buildings with central air conditioners or heating systems and naturally ventilated buildings. The thermal adaptation of naturally ventilated buildings to the outdoor climate, which encompasses a wide range of temperature and comfort conditions outside the thermal comfort zone as defined by standards, requires occupants to monitor outdoor temperature changes closely. In centrally air-conditioned buildings, humans adapt to thermal conditions through adjustments in clothing and air speed, which are most noticeable at temperatures ranging from 22°C to 24 °C. However, they become intolerant to temperatures that fail to meet their expectations. Optimization of energy and use of an adaptive mechanism in designing and operating buildings with individuals having control over the thermal comfort parameters [68]. The study on adaptive thermal comfort, conducted in a climatic chamber, aimed to analyze the influence on physiological acclimatization. It examined whether the length of time spent in an air-conditioned or naturally ventilated building environment demonstrated the adaptability of people in warmer conditions and their ability to adapt to a naturally ventilated environment. A personalized cooling system designed to create a microclimate around the person could optimize energy use and enhance thermal comfort. The increased air velocity for cooling the body indoors, tested in a climate chamber, enhanced thermal comfort at 30 °C. With the use of photovoltaic systems, energy savings of up to 40% can be achieved, considering an indoor comfort temperature range of 15–30 °C and a relative humidity of 70%. The study on thermal neutral temperature with the mixing of the air distribution like ventilation, displacement ventilation, and stratified ventilation, at varied global locations demonstrated the

effect of using a fan with the natural wind and different fluctuations in the air flow frequencies to attain thermal comfort.

A results of field studies with regression analysis by Richard De et al. in real-world building in diverse climate zones justifies adaptive model. The research method uses objective data having physical measurements of indoor and outdoor environments parameters like air temperature, radiant temperature, humidity and air speed and subjective data with questionnaire responses from occupants. The study demonstrated energy efficiency with the adaptive model, thereby justifying the use of wider temperature set points in naturally ventilated buildings. Promotes sustainability with mixed-mode and naturally ventilated buildings that work in harmony with local climates. Has improved occupant satisfaction with personal control on opening and closing windows based on contextual comfort. Integrates with international comfort standards, such as ASHRAE Standard 55 and EN 16798. Thus, the adaptive model is human-centric, contextual, and ecological, recognizing people as adaptive organisms with a more accurate framework for designing comfortable buildings that save energy [69]. Parsons conducted the study on human thermal environment using the heat balance equation to analyze the thermal situation, suggesting that humans are susceptible to heat stress, which involves the physiological inability of the body to maintain its temperature within the normal range required for physiological performance [70]. The heat stress can cause a negative impact on life, behavior, and productivity due to the comfort conditions. The use of air conditioning could be a solution to the problems of uncomfortable situations, which require a high amount of energy. The stipulation for buildings or indoor spaces is to have summer comfort at 26°C to 28°C with a relative humidity of 70%. Humans require energy to work, produce heat, and maintain an internal body temperature of around 37°C [67]. The level of heat, whether high or low, has an impact on the body, causing discomfort. Both environmental and personal factors influence thermal comfort; it is worth noting that a suitable thermal environment is essential for maintaining physical and psychological health, as well as positively impacting productivity [68]. Manzano-Agugliaro et al. suggest the bioclimatic design which involves adaptive approach to comfort considering human factor play an active role in energy saving and connection with environment [26].

1.3.3 Tools to develop design strategies for thermal human comfort

Different bioclimatic diagrams are used as tools for determining comfort levels. Victor Olgyay's bioclimatic chart facilitates comparative analysis of climates, synoptically displaying the factors affecting human comfort. Used as a tool to determine comfort levels at exterior and interior, with the thermal comfort index calculated using the relative humidity and the temperature values of the indoors, also adopted by ASHRAE, but does not directly address the effectiveness of the building in meeting human comfort [71]. The first step in bioclimatic design is analyzing climatic data, graphing the data using a computer-aided tool, and conducting simulations, which allow for more accurate approaches. Humans are comfortable at 20°C-26 °C, 20-80% RH, referred to as 'Comfort Zone' on the psychometric chart by Givoni [26]. A partial description of comfort provided by this and other variables includes radiant temperature, airflow rate, clothing, and metabolic rate (activity level).

- Baruch Givoni's building bioclimatic chart utilizes the same parameter to evaluate and define the characteristics of Graphic Evaluative Frameworks (GEFs). Figures are generated for the visualization of climate data, enabling the development of design strategies to achieve human comfort within buildings based on the divided zones in the diagram.

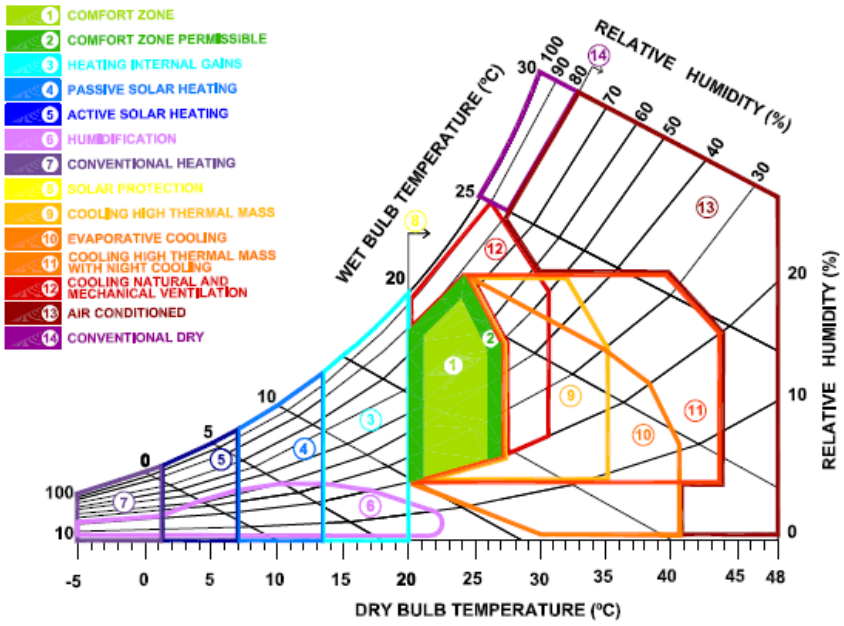


Figure 23: Psychometric chart adapted from Givoni, [26].

The dry bulb temperature is represented on the X-axis, air humidity on the Y-axis, and the psychometric curve with the relative humidity. The 14 zones in Figure 23 show associated architectural strategies adopted to shift the environmental condition to the ideal comfort zone [26]. The location's climatic conditions must be analyzed to plan the possibilities of a bioclimatic architectural strategy. As shown in the diagram, the environmental conditions of the area where the scenario is to be designed in a zone, if found outside the comfort zone, appropriate passive or active architectural strategies can be implemented. Passive strategies are considered at possible levels, and low energy-consuming and energy-efficient solutions are adopted to the best possible level [38], [46].

- Contemporary computational approaches, incorporating software tools like SOALR-5, to predict thermal mass and heat gain/loss based on hourly weather data used during the design stage of the prototype. Software tool CLIMATE CONSULTANT, Energy design software tool ECOTECH, and AUTODESK Weather tool for more detailed visualizations on climatic implications in building. The weather tool summarizes the hourly positions of climate on the psychrometric chart and displays a cumulative chart with a color gradient. Givoni's rule of thumb is encapsulated in the Climate Consultant and weather tool, which enables an interactive view by allowing users to manipulate variables. Comparative studies are possible with the software by plotting an expanded range of data points [72]. The simulation tool is a means to predict performance during the design stage; however, design knowledge requires post-occupancy evaluation, which can be informed by the building's construction and subsequent occupancy.
- Passive design strategies based on climate by Cooling Degree Days and Climate Year demonstrates a combination of the climate season with classification based on the cooling degree days at 26 °C over a year. The combination of the climatic season for the Middle East is as indicated below:

-Very hot and dry Climatic Year: S2 + S4 + S5 + S6 (Riyad, Medinah)

-Very hot and humid Climatic Year: S2 + S3 + S5 + S6 (Dubai) and S2 + S5 + S6 (Doha)

-Extreme Hot Climatic Year: S5 + S6 (Jeddah, Makkah)

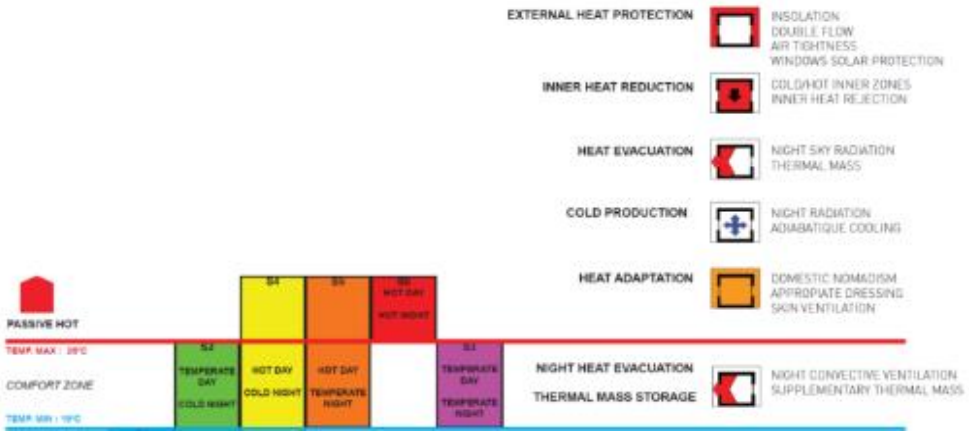


Figure 24: Strategic directions and Classification of architectural actions for a very hot climate (AA) [62], [73].

The suitable architectural actions for a very hot climate season can be identified from the strategic direction and classification chart for architectural action, as in Fig. 24, showing the suitable common architectural actions for the extreme warm climate. The hierarchy in possible architectural action based on local context has been simulated and verified for its payback period. The architectural actions for the climate season developed the basic principles of bioclimatic architecture, considering the project site's challenges and local context, which enabled the achievement of energy-efficient designs [62], [73].

1.4 Architecture in the Extreme Warm Climate

1.4.1 Vernacular and climate-adapted architecture for extreme warm climates

a) Form, orientation and ventilation

The building's shape, form, and orientation significantly affect the indoor climate and thermal conditions by influencing how exterior surfaces absorb solar heat and how light and ventilation openings are optimized [40]. Passive design strategies help create a comfortable indoor environment with minimal dependence on active systems, reducing energy consumption. Adjusting the building to suit the local outdoor climate yields a unique indoor setting with enhanced thermal performance. Elements such as shape, orientation, and the wall-to-window ratio for controlling solar radiation, as well as the materials used for walls, floors, and roofs, all contribute to how the building interacts with its external environment [38]. Furthermore, Feriadi & Wong examined residential buildings in Indonesia and found that strategic building orientation,

combined with passive ventilation, could lower indoor temperatures by 2–3°C and reduce dependence on air conditioning by up to 40% [74].

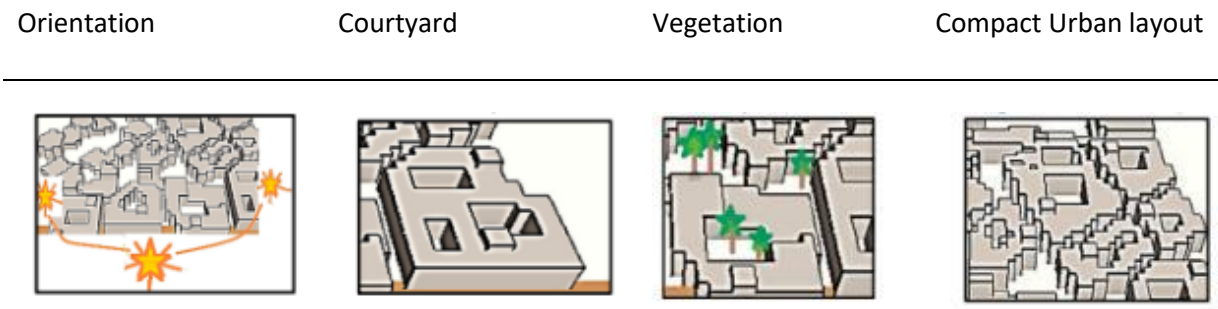


Figure 25: Views representing passive design approaches used in traditional residential building in the extreme warm climate of the UAE [75].

Additionally, air movement can enhance comfort in hot climates through passive methods such as thermal mass and evaporative cooling. Proper placement of walls, building masses, and openings, as shown in figure 25, according to the sun's path, reduces solar gain. Courtyards improve ventilation through the stack effect. Vegetation enhances thermal comfort by means of evaporative cooling. The compact urban layout increases shaded areas and exposure to direct sunlight, thereby decreasing solar heat gain [42].

b) Designed elements for Sun protection and ventilation

The building measures in this climatic zone aim to protect the living environment from the extreme ambient heat. The principle for cooling can be in two methods: First, the temperature in the building is lowered by adiabatic cooling with the evaporation of water, and second, warm air is exchanged with cool air. The air exchange creates a comfortable sensation in the human body, with air movement being an aid to lowering the body temperature. Under normal circumstances, the warmth in the human body is emitted with 30% as convection, 45% as radiation, and 25% as evaporation. The air movement increases convection and evaporation, dry heat causes precipitation with water dissolving in the air, leading to evaporative heat loss as a practical measure. In the hot and dry climate, perforated and air-permeable coverings set in windows could maximize natural ventilation. Wooden lattice known as Mashrabiya is used in window openings in traditional buildings in Egypt and the Middle East. Use of Oriels as a feature, the term meaning ‘a place to

drink' with unglazed clay jars kept in the niches filled with water, the water evaporates and cools the incoming air there by creating comfort with evaporative heat loss [76].



(a) (b)

Figure 26: (a) Mashrabiya providing shading from the sun and good ventilation, (b) The effect of Mashrabiya / jail in the indoors [76].

The Mashrabiya as shown in figure 28 works on the following principles:

- Controlled and diffused supply of daylight
- Protection from the direct solar radiation
- Air velocity control with different sizes of lattice apertures
- Creates privacy with having an outside view and a limited inside view due to light contrast.

Mashrabiyas with internal courtyards, ventilation towers, and additional superstructures feature mashrabiya oriented in the direction of the sun and wind. These superstructures serve as light sources to deeper rooms and sources of natural ventilation. They are used in traditional buildings for accelerated air movements and increased cooling effect.

c) Principle of continuous air flow in buildings

The wind catchers shown in Fig. 27 (a) and (b) are installed on rooftops of traditional buildings, directing air through ducts into living spaces. In Iran, they are called 'Badgir,' and in the UAE, they are known as 'Barjeel.' The openings of these wind towers face the prevailing wind direction and feature various geometries, like the octagonal tower seen in the Iranian city of Yazd, which can reach up to 30 meters in height. They channel cool air into rooms and adjacent courtyards,

exhaust high humidity air, and supply fresh, evaporative cooled air during the day. At night, the cooler air helps to cool the large buildings, preparing them for the next day.



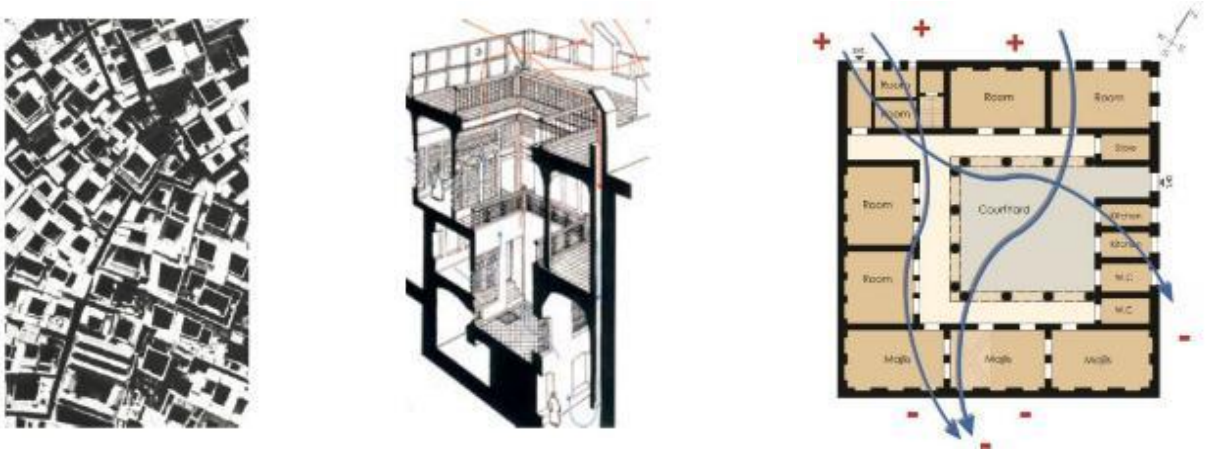
(a) (b) (c)

Figure 27: Wind catchers (a) 'Badgir's' of Iran, (b) 'Barjeels' in Al Bastakiya Dubai (Source: [76] (c) Horizontal Barjeel at Al Hamadiya School, UAE [75].

In the hot and humid regions with temperatures above the body's temperature, comfort levels are achieved by evaporation and perspiration, which requires maximum air movement led by large wind catchers that are open in all directions. The wind catchers are kept high to have the least dust in the building. The towers are aligned, not being hindered by the neighboring buildings [76]. The horizontal barjeels as in Fig. 27 (c) opens to rooms connected to verandah opening to the courtyard, acting as a thermal modifier [75]. Givoni (1998) showed that in hot arid climates, proper orientation and cross-ventilation can reduce indoor air temperatures by up to 4–6°C, compared to poorly ventilated structures. His research highlights the importance of narrow building forms aligned with prevailing winds to maximize natural airflow [46].

d) Courtyards

The courtyards, as shown in Fig. 28 (b) and (c), bring cool air into large, massive buildings in a hot and dry climate, with arcades providing shade and making the hot day temperature more bearable. At night, the cool air sinks and becomes trapped in the yard, cooling the adjacent building mass. During the day, the shading does not let them get heated up very much, with the buildings shading each other in the cluster. The cooler air, being heavier, penetrates the rooms adjacent to the courtyards. This works on the principle of pressure gradient between the warm and cold air.



(a) (b) (c)

Figure 28: (a) Courtyard houses in Morocco, (b) Conventional ventilation in a courtyard house, (c) Courtyard house Al Bastakiya, Dubai [76].

The cooler night air displaces the warm air in the courtyard; during the day, the warm air above encloses the cool air in the courtyard. The courtyards are proportioned and dimensioned to provide self-shading, which is particularly beneficial in climates with significant temperature differences between day and night. The walls facing the courtyards need to be insulated or massive. The opening sizes are kept small to prevent the stored cool air from escaping. In urban areas, as shown in Fig. 28 (a), narrow street alleys hinder strong air movements [76]. Similarly Taleghani et al. conducted simulations of traditional courtyard houses in warm climates and found that optimized courtyard dimensions and natural ventilation strategies could lead to a 35–50% reduction in overheating hours during summer [77].

e) Use of large building mass to store cold night air temperature and disperse through air pockets

Convection cooling is another principle used in courtyards, influenced by both the building height and the courtyard size as shown in Fig. 29. If it does not fully shade during the entire day, the exposed ground in the courtyard warms up, rises, and creates airflow in the building, helping disperse the cold air from the wall massing into the surrounding air. This results in air circulation into the house, with hot air rising upward in the courtyard. During the daytime, the courtyard cannot be used due to sun exposure, but the stored heat at night provides a comfortable temperature.

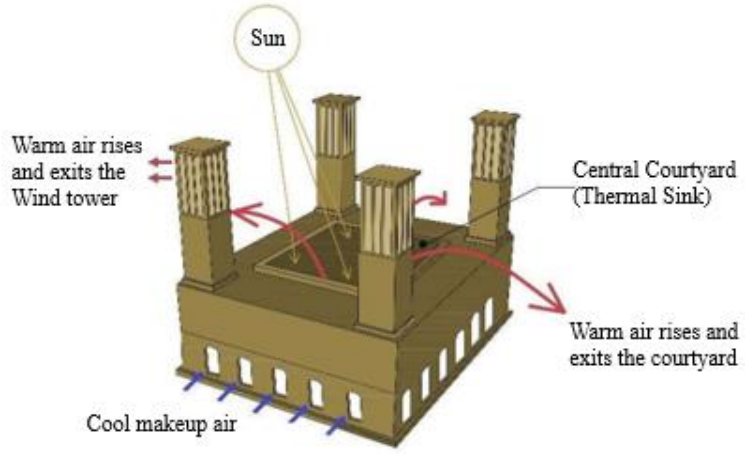


Figure 29: Air circulation using the courtyard and wind tower [16].

f) Vegetation and permeable shading for protection and air circulation

Large trees with a projecting crown are a simple form of shading as in Fig. 30 (a) and (b); this also acts as a gathering space. In the absence of trees, planted wine palisades serve the purpose. Sun sails or awnings, straw mats, linen sheets, and palm fronds stretched as in Fig. 30 (d) over the narrow winding alleys protect against the sun in the dry, hot Arabic regions. This, being permeable, creates air circulation. In some cases, the use of ropes to pull the linen lets a slight breeze move into the building as in Fig. 30 (c) [76].



(a) (b) (c) (d)

Figure 30: (a) Vegetation creating thermal comfort to private courtyard in residence, (b) Vegetative shading in public courtyard, (c) Compact urban pattern with shaded path to improve thermal performance, (d) Wide corridors shaded with palm leaves in Souq Saleh, Ajman, UAE, [75].

g) Adiabatic cooling

Evaporative cooling is based on the principle of human skin cooling by perspiration. The warmth from the ambient air is drawn with the evaporation of water, creating a cool sensation to the skin.

Hanging moistened fabric over the air inlet in exterior walls cools the incoming air and eliminates dust particles. The use of an unglazed jar with water for the cooling effect and humidifying the dry air is a benefit of adiabatic cooling in the hot and dry regions. In some hot and dry cities like Isfahan in Iran & Damascus in Syria, water channels and viaducts keep walls wet, constantly increasing the cooling efficiency. Additionally, stone surfaces with water turbulence, water fountains, and water-filled basins enhanced the cooling effect, creating a comfortable environment, providing a refreshing sensation, and fostering a positive psychological impact on human minds [76]. The heat exchange with the climate moderator, with regulated air through evaporation by using water fountains and water basins, channels minimizes heat reflection and reduces solar heat gain [5].

h) Thermal mass

Massive walls reduce the warming from solar radiation, with the incident energy warming the building material and slowly spreading to the inside. Clay bricks and adobe walls were used as they have storage capacity, providing a comfortable temperature during the cool nights. The traditional clay mosque in Mali, West Africa, has cooler interiors compared to the outdoor areas of the building as in figure 33 [76].



Figure 31: Clay Mosque at Mali, West Africa, [76].

The Table 4 shows the principles and solutions related to the climate-adapted architecture in the dry climate as.

Table 4: Principles and solutions related to the climate adopted architecture in the dry climate

Sr. No	Principles for the Hot & Dry Desert Climate	Solutions
1	Sun Screen	Shading is required in open areas and over buildings and urban areas with overhang roofs, grids, pergolas to maximize protection from solar radiation
2	Insulation	Use of material with thermal mass and insulation to lower the temperature peak in the day
3	Natural Ventilation	Maximize natural ventilation to make maximum gain in comfort conditions with air velocity
4	Heating	Stored heat in the thermal mass can be used at night to create comfort conditions
5	Cooling	Use of adiabatic cooling, natural ventilation, and thermal mass storage
6	Sun Orientation	Block the direct sun and minimize the solar heat gain

These results demonstrate that thoughtful design choices particularly related to building form, orientation, and passive ventilation are not merely aesthetic or theoretical, but have a measurable impact on improving thermal comfort in hot climates.

1.4.2 Potentials in incorporating Traditional Principles into Modern construction

Traditional practices and building methods, developed over centuries based on local climate conditions, closely resemble future engineering solutions. These include using adiabatic cooling systems in compact setups with heat exchangers that remove excess humidity, awnings—both static and dynamic sun protection screens—self-cleaning and sun-protected coatings, and insulated, fire-retardant glass for building envelopes. These solutions are now achievable thanks to advances in construction, manufacturing, and material technology specifically designed for climate-based protection and performance. They enhance comfort and help buildings better adapt to extreme weather conditions. Today, global standards aim for consistent comfort levels worldwide, supported by unified international codes. However, achieving the same comfort levels

and conditions in buildings is no longer feasible with traditional methods, especially considering the structural and space requirements of low-rise and multistory residential buildings. New approaches developed and implemented in bioclimatic architecture for desert climates will be examined and evaluated in the upcoming chapters. Research on developing sustainable practices in the Arab world [74] highlighted the need for integrating regional approaches that incorporate all aspects of sustainable architecture, considering the local environment, social, and cultural values. The study comparing contemporary and traditional houses in the UAE found that the former usually features a Western model with an outward-facing style. But the region's conventional norms and social values called for inward living, which was reflected in traditional houses being in harmony with people's way of life, respecting social values, and working well with the surrounding environment [74]. This aligns with the idea of 'design with nature' [75]. Using passive strategies and solutions in hot climates promotes optimized energy use and savings, reducing climate emissions. Buildings with climate-adapted designs decrease reliance on mechanized technology, making them easier to operate and maintain.

The commitment of the UAE to decarbonizing its building sector with the target to reduce greenhouse gas emissions by 81.4% by 2030 and the UAE's net-zero climate targets by 2050. The government and private sector are promoting sustainable building practices in residential projects like The Sustainable City [9]. There is a need to incorporate passive design using lessons from the vernacular architecture considering the climatic conditions of the area [16]. In the hot and arid climate most of the energy load are from mechanical systems for cooling, a potential of reduction in cooling load and annual energy consumption with use of solar shading, passive cooling with optimal thermal comfort using passive strategies [62], [78], [5].

1.5 Chapter Summary

Chapter 1 covers bioclimatic principles, strategies, and concepts, emphasizing the benefits of bioclimatic architecture. It describes strategies for extremely hot climates, offering insights into traditional building practices in hot environments and providing guidance for modern construction. The factors affecting thermal comfort in buildings are examined analyzing the modern materials and construction technologies that enhance comfort in extreme climates. The study on traditional architecture to understand the potentials to integrate its principles in modern construction

integrating bioclimatic architecture for the desert climates. This will enable to suggest recommendations for future design and construction in the extreme warm climate. Research highlights the importance of integrating sustainable architectural practices in the Arab world aligning to social norms with ecological harmony, supporting passive strategies that reduce energy use and emissions.

Quick summary of Chapter 1

- Traditional building practices in hot climates offer insights for modern construction, paralleling advanced systems like adiabatic cooling, sun protection screens, and climate-adapted building envelopes.
- Modern materials and technologies enhance comfort in extreme climates while meeting today's global standards for indoor conditions.
- Traditional methods alone cannot meet the demands of contemporary multistory buildings, requiring integrated bioclimatic solutions.
- Bioclimatic architecture in desert climates, such as in the BaityKool prototype, will be studied to evaluate performance and offer recommendations for future construction.
- Research stresses the importance of integrating local environmental, social, and cultural values into sustainable architectural practices in the Arab world.
- Traditional inward-looking housing in the UAE aligned better with social norms and environmental harmony, supporting passive strategies that reduce energy use and emissions.

Chapter 2:
BaityKool Living Lab (BK-Lab) as a Tool for Experimentation on Bioclimatic Architecture for the Extreme Warm Climate

Chapter 2. BaityKool Living Lab (BK-Lab) as a Tool for Experimentation on Bioclimatic Architecture for the Extreme Warm Climate

Following the theoretical foundation established in Chapter 1, which identified critical bioclimatic strategies for mitigating thermal stress in extreme warm climates, Chapter 2 introduces the BaityKool prototype as a full-scale experimental implementation of these principles. Chapter 1 demonstrated, through literature and climate analysis, the importance of passive cooling, thermal mass, envelope insulation, and adaptive ventilation in enhancing thermal comfort while reducing energy demand in arid environments. These findings are operationalized in the BaityKool design, which combines compact geometry, a vegetated courtyard, high-performance multi-layered envelope, and hybrid passive-active systems. This chapter outlines the architectural methodology, material selection, and environmental simulations used to translate theory into built form. Moreover, it presents quantitative performance data, such as U-values, energy simulation outputs, and thermal comfort indices, collected during the Solar Decathlon 2018 and ongoing Living Lab experiments in Dubai. In doing so, Chapter 2 validates the feasibility and effectiveness of bioclimatic architecture under real-world constraints, offering a critical bridge between theoretical design strategies and empirical performance outcomes

2.1 BaityKool Project and its transition as a Living lab

2.1.1 Background and Context

The BaityKool Project, a self-sustaining, eco-responsive habitat designed for the extreme warm climate of the UAE, was developed by a multicultural and multidisciplinary team. The students, faculty advisors, and professionals from Arts et Métiers in Bordeaux (ENSAM), the Architecture and Landscape School of Bordeaux (ENSAP-Bx), Al Najah National University (Palestine), and Amity University Dubai collaborated to form the initial proposal in 2016. In 2018, the final assembly of the prototype building was completed in 15 days at the SDME 2018 competition site (Solar Decathlon - Middle East at Mohammed bin Rashid Al Maktoum Solar Park, Dubai [79]. The prototype and its systems were tested for full operations. After passing all inspections, the sustainable houses were evaluated for the 10 contests of the Solar Decathlon over ten days. The evaluation included contests categorized by SDME as Juried, Monitored, and Monitored / Measured tasks. There were six groups of jurors, comprising international experts, who evaluated the Juried contest. Throughout the ten days of the SDME competition, teams were assigned to perform typical household tasks and chores. Simultaneously, the project was continuously

monitored with regard to indoor environmental quality, including air temperature and energy performance.



(a)

BaityKool in SDME 2018 (https://baitykool.com/sdme2018.html competition phase)



(b)

BaityKool in The Sustainable City (https://baitykool.com/BKinTSC-en.html experimentation phase)



(c) Plan of BK prototype at TSC post competition as a living lab

Figure 32: BaityKool prototype (a) BK in SDME 2018, (b) BK-lab in The Sustainable City as experimental platform (c) Plan of BK prototype as living-lab, (Source: Author)

After the SDME 2018 competition, the BaityKool project shown in Figure 34 (a) was integrated into The Sustainable City in Dubai, UAE, in 2021 as a platform called BaityKool Lab, shown in Figure 34 (b), to pursue R&D initiatives focused on innovation and technology. The prototype then functions as a Living Lab, serving as a tool to experiment with bioclimatic architecture designed for the extreme weather conditions of the UAE.

2.1.2 Purpose of BaityKool as a living lab

The BaityKool platform was integrated into TSC in Dubai as a Living Lab, an experimental platform designed to test and analyze the performance of a prototype that reduces energy needs through passive strategies and promotes healthy living with bioclimatic architecture. An extension of the SDME 2018 competition was introduced, featuring a series of R&D initiatives on innovations and technologies developed for extremely warm climates. Additionally, this system aims to provide real-time intelligent management of building operations, developed based on seasonal and thermal comfort needs. This approach seeks to reconcile the goal of minimizing energy consumption with the optimization of solar energy production through bioclimatic design strategies, such as passive cooling, adaptive shading, and thermally efficient materials, which mitigate heat gain while maintaining thermal comfort. By leveraging eco-responsive architectural solutions rooted in regional climatology and cultural contexts, the system aims to reduce dependence its reliance on active cooling, thereby lowering both embodied and operational carbon emissions. The primary purpose of the experiments at the BaityKool living lab is to evaluate the effect of passive design interventions on reducing peak cooling loads and enhancing solar energy utilization in extremely warm climates.

2.1.3 Key goals of BaityKool with Bioclimatic Architecture for the Extreme Warm Climate

The BaityKool prototype was designed as a biological ecosystem as in figure 35 that serves as a co-working and co-living space, tailored to the culture and extreme weather conditions of Dubai.

The key goals of architecture, engineering, and construction are:

- An intelligent building adapted to its environment across all seasons [80].
- Achieving optimal energy equilibrium by harmonizing minimal consumption with solar generation through passive design and hybrid systems, ensuring superior building performance in extreme warm climates [81], [26].

- Integration of biodiversity in architecture with food production and vegetation [82], [37].
- Bioclimatic passive design strategies combined with hybrid systems, by integrating productive green infrastructure, enhance building performance and improve microclimate regulation [83], [56].
- Achieve net-positive biodiversity impact in extreme warm climates [44], [84].



(a) (b) (b)

Figure 33: (a) See view of Patio from North side of BaityKool, (b) See view of the Patio from South side of patio view from indoor corridor through the aquaponics wall aquarium, (c) See view of the solar mobile pergola looking up from the patio (roof PV solar production field)

2.1.4 Methodological Framework for Design Validation

This subsection outlines the structured methodology adopted to translate the theoretical bioclimatic principles, introduced in Chapter 1, into a built prototype and to assess their effectiveness under real climatic conditions. The aim was to develop a scientifically grounded workflow combining architectural design, simulation-based performance prediction, full-scale prototyping, and post-occupancy monitoring. This methodological sequence is divided into five key phases as shown in Fig. 34.

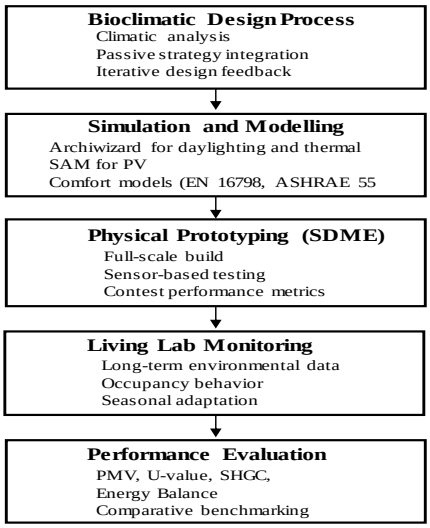


Figure 34: Methodological Framework used in BaityKool platform

- **Bioclimatic Design process:**

The design took inspiration from the 'Traditional residential architecture'. A building form designed for enhanced environmental control, featuring a courtyard, minimized exterior openings, and maximized courtyard openings. The house was designed using passive strategies, featuring a modular concept with 'Flexibility', a design that can adapt to fit any scenario, respecting privacy and personal needs. An 'Innovative Courtyard' is shaded by building mass and a moving solar pergola, which provides shading during the day and allows increased air movement at night as it opens to the side. The 'Outdoor Landscaping' features a green heart at the courtyard, complemented by a stepped terraced roof. The front wooden claustra serve as a threshold, providing vegetative shading that filters the dust in the air and creates a visual comfort, as well as evaporative cooling from the moist planter bed. Lastly, the design for 'Collective Housing' features a cluster of dense courtyard houses that drive light and air from the open spaces, thereby reducing solar heat gain. The design was developed after several iterations of layouts and architectural form as a living& co-working space that transforms from an office during the day to a residence at night.

Engineering and Construction design features an Innovative, multi-layered, high-performance UHPC wall composition made from eco-friendly materials, offering thermal properties and efficiency to reduce energy consumption and ecological impact. Addresses the challenge of quick construction assembly and disassembly. The design's energy efficiency is achieved through compactness and an envelope system that guards against harsh sunlight. It employs passive and semi-passive solutions, including orientation, water and plant use for evapotranspiration, and natural cooling with a day and night strategy. Shaded windows with limited opening sizes on east and west-facing exteriors minimize solar heat gain. The U-shaped architectural form, featuring a central courtyard with a retractable solar pergola, shields the interior from the sun. At night, it utilizes diurnal temperature differences by evacuating heat through natural ventilation created by the architectural volumes.

Energy Efficiency measures with passive and semi-passive measures with efficient active systems developed, like the 'Radiative sky cooling system' with thermal radiators mounted on roof cools water with the outdoor temperature using water and heat exchanger. Integrating the radiative sky cooling with the dimensioning method HVAC system combining several technologies to minimize

energy, water consumption and reduce environmental impact. Innovative biological water treatment system 'Lumbrifilter' integrated with the Aquaponics module composed of a fish tank with zip row towers embedded in the wall separating the patio area and the corridor of the house. A 'Building Integrated Photovoltaic' system with architectural integration on roof as patio cover and facade. The photovoltaic panels use more efficient biomimetic solar cells inspired by nature, which produce smooth electricity from morning to evening.

Innovation for the environment with Bio-sourced materials is selected based on an environmental footprint study, prioritizing recyclability and reusability. Greywater management and vegetation design aim to create an ecosystem that brings freshness to the heart of the prototype—the patio (courtyard). Native plant species suited to the regional climate and requiring less water are chosen. The protective roof features vegetation following the stratified principle of an oasis. Its stair-stepped shape has the upper layer with hardy plants that need less water and resist heat and sunlight. The lower layer contains less resilient plants, with the roof's shape allowing water to flow from the upper to the lower terraces. An intelligent automatic watering system, linked to a real-time weather station, enables autonomous, metered watering to optimize water use. The vertical farm at the aquaponic system with the fish tank is an innovative way for food production at the prototype.

- **Simulation and modelling**

Building performance simulations with Eco-efficiency to save energy, an intelligent energy-saving approach adopted with eco-efficiency, 'Creating more good services while using fewer resources and creating less waste and pollution'. Thermal house behavior was simulated for the best architectural design. The software forecast results for night cooling and passive strategies, providing an energy balance. A comprehensive house performance test was conducted for the 'Electrical energy balance', with simulation results giving annual production by the PV modules with consumption. The energy balance report as in the BaityKool project manual [22] indicated the PV generates as much energy needed by electrical load of the BaityKool house annually. 'Structural Design' considering loads and design of building elements: foundation, wall, beams, joints and roof truss. House 'HVAC' simulation with cooling load requirements for the designed innovative system. The house performance annual simulation with passive analysis determining the thermal requirements and predicted indoor air temperature and cooling loads using passive

strategies. Utilization of smart applications for real-time monitoring of energy, water management, HVAC systems, room temperature, relative humidity, and air quality.

- **Physical Prototyping (SDME)**

Project management, pre-SDME, includes planning for management of the multi-cultural team from Bordeaux, Dubai & Nablus. The logistics strategy involved work packages with multiple design teams, spanning from conception to full-scale built-up assembly during the SDME competition phase, including pre-fabrication in France and the first assembly in Dubai and final assembly at the SDME competition site. The prototype was tested for the contest during the competition period using sensor sensors with the house functioning to assess the performance.

- **Living lab monitoring**

Post SDME, the prototype was established as a living lab for a series of R&D initiatives centered on innovative technologies, long-term experimentations of occupancy behavior, and seasonal adaptation.

- **Performance Evaluation**

Real-world experimentation of the prototype in the extreme warm climate to assess the performance of the innovation and technologies of the systems. Validate the technical feasibility and economic viability and environmental benefits, conduct comparative benchmarking with developed strategies for energy balance with proven solutions. Develop recommendations for eco-friendly, energy efficient and sustainable designs suiting to the extreme warm climate.

2.2 The BaityKool Project

2.2.1 Concept & Design Strategies

A compact, flexible, modular plan that can adapt to different scenarios, respecting the privacy of the occupants and meeting their personal needs. The architectural design inspired by Dubai's historical architecture, with a compact U shape, closed on the outside and open on the inside. The layout is planned around the central 'patio', the green core courtyard as in figure 35 (c). The U-shaped layout has a private side with two bedrooms on the west-facing side one of which as seen in Figure 35 (b), a non-private side with the living and dining as in Figure 35 (a), and a semi-private multi-use kitchen space on the east facing side. Both sides are connected by a service area having a washroom and a technical room space. The 'green patio' (courtyard) in Figure 35 (c) at the center connects the two sides visually and encourages diversification of activities.



(a)



(b)

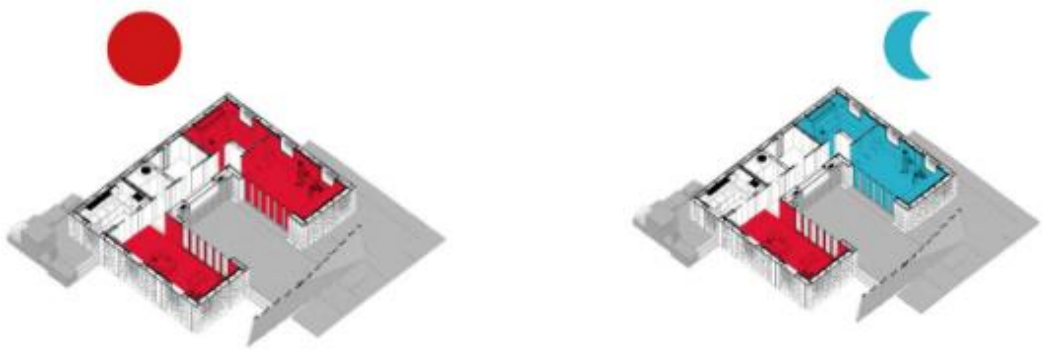


(c)

Figure 35: (a) See view from South of the living co-working space – East wing of BaityKool, Living, (b) See view from South of the Bedroom co-working space West wing of BaityKool, (c) See view of patio from North-West side of BaityKool.

The larger sliding folding doors facing the courtyard on either side of the room allow for free circulation and ensure a continuity between the rooms when the house transforms into a co-working space, as in Figure 36 (a). The living room could change to a common working area and the bedrooms as more intimate working offices. The interiors of the house facilitate its

transformation from a workspace to habitat as in Figure 36 (b) or even both as indicated with the space dynamics.



(a)

BY DAY

Prototype functioning as a **CO-WORKING** space

(b)

BY NIGHT

Prototype transforms to a **HOME**

Figure 36:Space function dynamics of BaityKool prototype (a) across Day, (b) across Night, [22].

2.2.2 BaityKool Environmental Design Principles & Characteristics

The architectural design of BaityKool integrates vegetation across the roof, walls, courtyard, and claustra to mitigate urban heat island effects, enhance insulation, and foster biodiversity [22]. The detail of this concept is presented in [85]. A central courtyard improves physical and visual connectivity with nature, contributing to occupant well-being. The U-shaped, modular layout accommodates functional flexibility and promotes cross-ventilation, while the compact massing optimizes shade and material efficiency. The building is designed to adapt to Dubai's extreme climate through passive and semi-passive strategies.

Orientation, window placement, and internal courtyards with shading systems reduce solar gain and enhance indoor thermal comfort. Solar control is achieved through an arid mineral envelope, a UHPC screen, and automated blinds managed via a Building Management System (BMS). A dynamic solar pergola further shades the courtyard throughout the year. Natural ventilation harnesses prevailing winds and is controlled through automated openings to reduce cooling loads. Daylighting is maximized via large, double-glazed, solar-control windows, reducing artificial lighting use while managing glare. Thermal mass elements like clay tiles and concrete floors store and regulate heat, while bio-sourced insulation minimizes heat transfer. Energy efficiency is

enhanced by photovoltaic panels placed on pergolas and façades, alongside passive thermal control measures. Graywater is treated and reused via bio-solar filtration and aquaponic systems integrated into the courtyard. Material selection prioritizes thermal efficiency and environmental responsibility, reducing both operational and embodied energy.

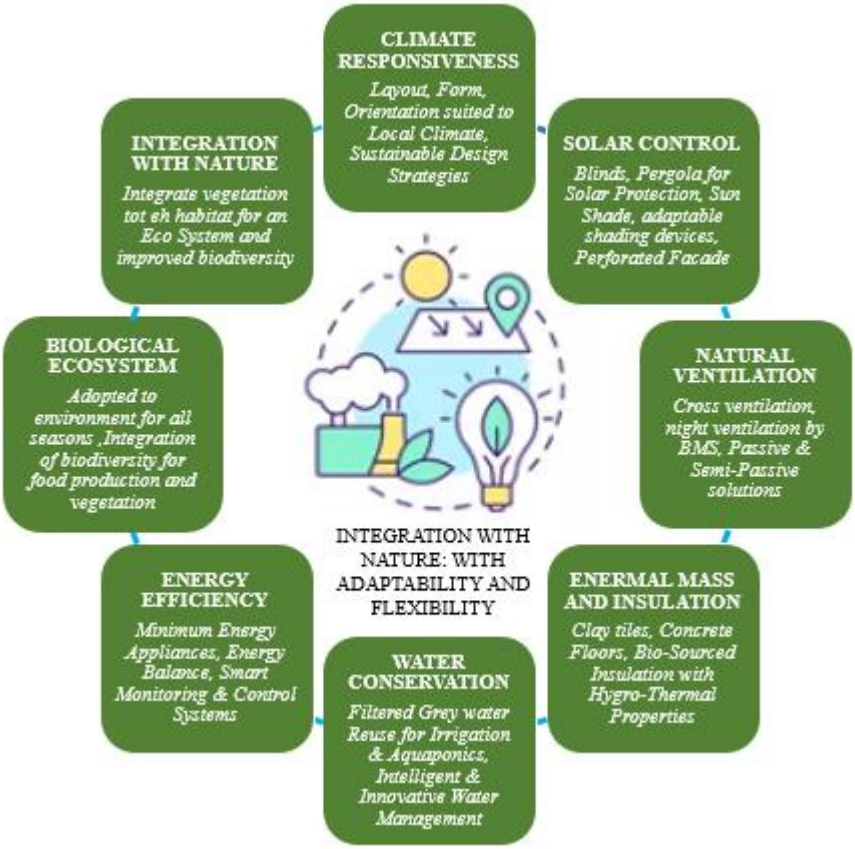


Figure 37: The concept of BaityKool design, [22], Author.

2.3 Bioclimatic features of BaityKool design and details

2.3.1 Compact Design layout with shaded Courtyard

The BaityKool plan features a compact U shape, encompassing a courtyard, known as the ‘Fena’, the green patio, as illustrated in Figure 33 (c), inspired by the traditional houses of the UAE region. The modular concept of space planning, along with the proximity of zones and their organization into private and semi-private spaces, allows for less space wastage during circulation. There is an optimum utilization of space and volume for living and working, and the indoor living and bedroom spaces open to the courtyard, which serves as a green patio, as shown in Figure 38.

The courtyard is naturally protected from harsh exterior weather conditions by the surrounding interior mass. The north-oriented opening of the courtyard minimizes exposure to direct sunlight, allowing diffused natural light to enter the patio without glare (refer to Figure 33 (b) for the patio view from the interior corridor of BK). The openings to the house are maximized towards the courtyard and minimized to the outside. The prevailing north and northwest winds passing through the courtyard allow for passive cooling. This maintains the level of good environmental control while also ensuring intimacy and user privacy in the interior spaces.

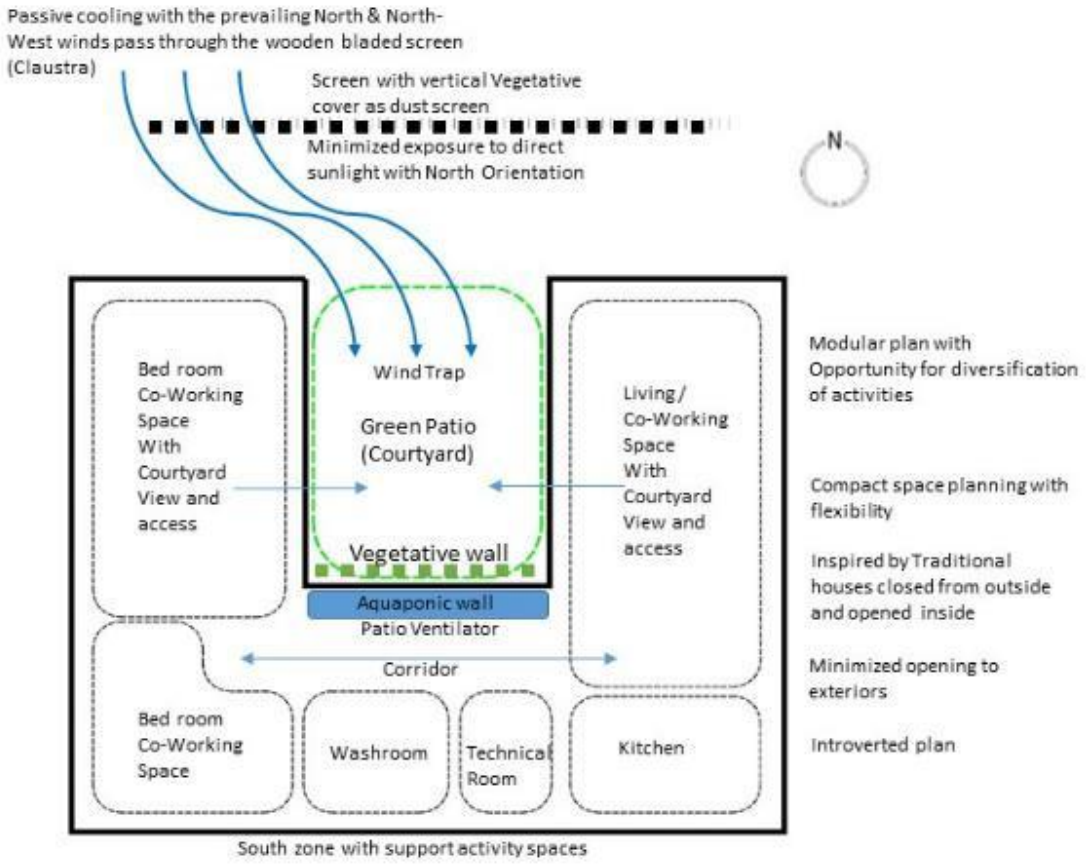


Figure 38: Conceptual plan with proximity and zoning, Author.

2.3.2 Form, Space, Order, and Orientation

The design features a U-shaped building mass with an inner shaded courtyard, as illustrated in Figure 38, and incorporates an adaptable shading device. The retractable solar pergola shields the courtyard during the day from solar rays. It retracts towards the rear at night, allowing natural air movement and providing occupants with direct visual contact with the night sky from the

courtyard. The building's form slopes inward to the courtyard on three sides, featuring stepped terraces for vegetation on the roof.

The slope allows rain and surface water on the roof to be drained towards the courtyard, where it is collected in a storage tank for biological filtration. The inward slope enhances air movement and improves the visual connection between the user at the patio and the green roof. The flat area on the top end of the roof has the radiative sky cooling panels installed on the east and west sides. The center block has the solar water heating panel.

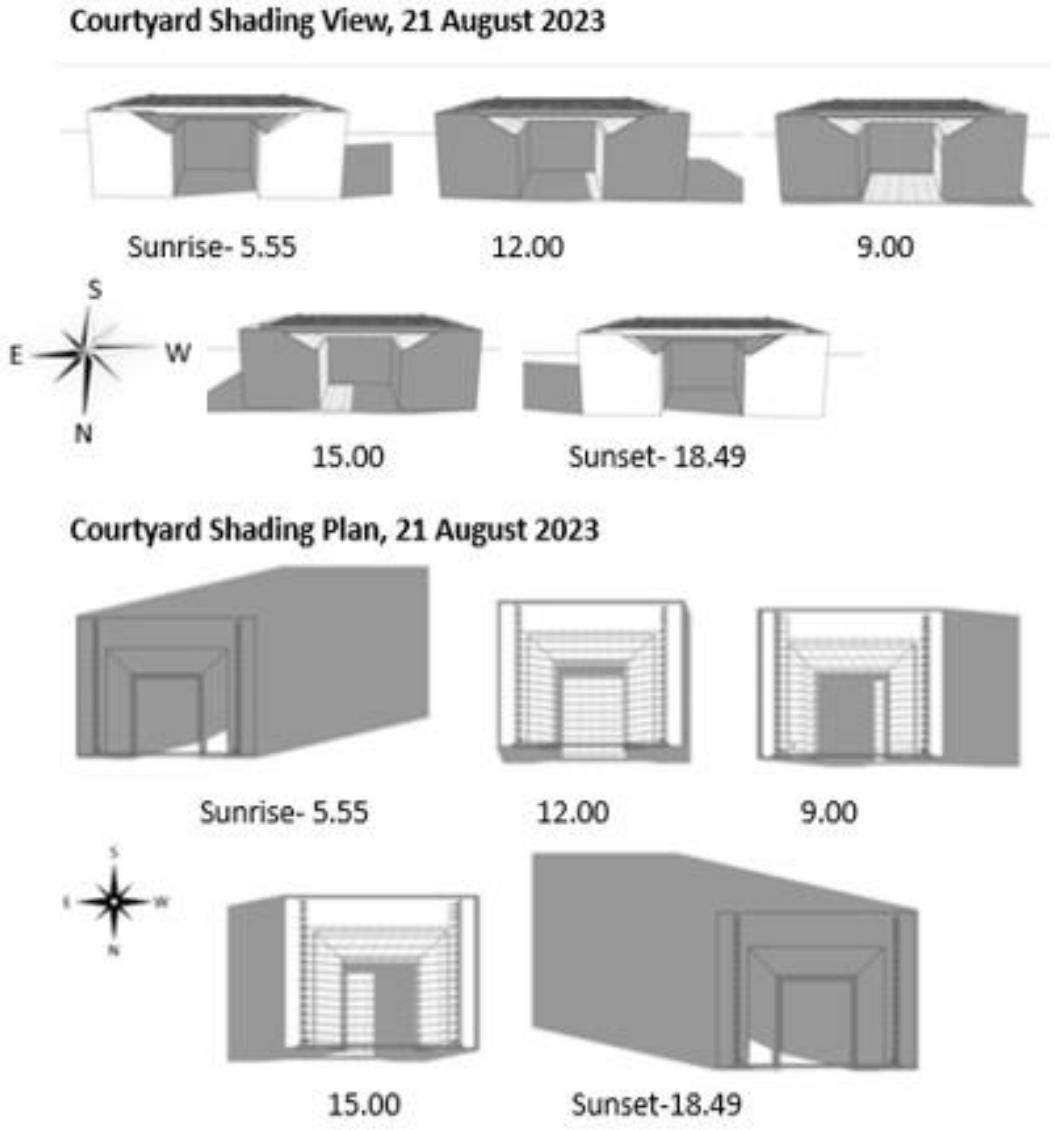


Figure 39: Shadow study for the Baitykool Architectural Form for a day in August 2023, Author

The inner courtyard shaded by the single storied building mass in a C shape form has its orientation takes advantage of the wind directions and solar shading based on the sun path as shown in Figure 39 shadow study. The courtyard takes advantage of the projected shadow of the building during the day, the north orientation protects house from direct sun. Additionally, the dynamic retractable solar pergola over the courtyard and the building roof acts as a protective exoskeleton as shown in the sectional elevation in Figure 40 adds shade and allows air to circulate naturally, an important element for heat control and to manage natural light in to the building.

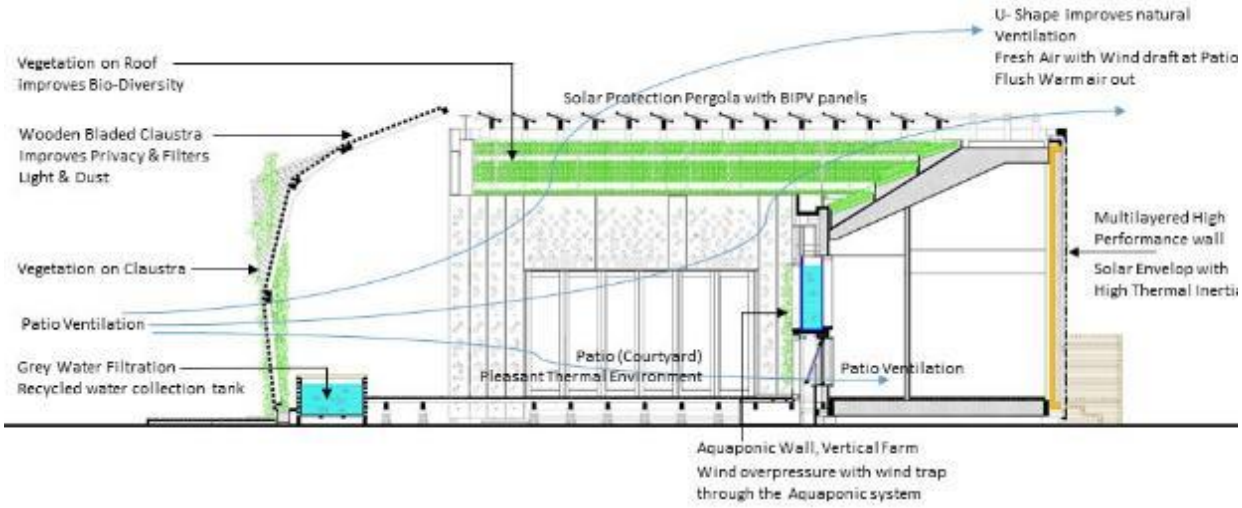


Figure 40: Sectional elevation of BaityKool prototype through the north-oriented claustra, patio, and washroom of the prototype, Author.

The courtyard's north-facing perforated façade, featuring wooden-bladed claustra, marks the entrance, as shown in Fig. 40. This creates visual privacy in the courtyard and allows wind drafts to pass through, enhancing the comfort of the space. The dynamic wooden pergola installed with the BIPV panels provides shade during the day and facilitates natural air movement. At night, the pergola retracts toward the rear, as shown in Fig. 41, increasing airflow. The opening of windows and patio ventilators enables hot air to escape due to the architectural volume, taking advantage of the cool night temperatures. The space's compactness, connectivity, and circulation support flexibility with improved cross-ventilation and air flow. Therefore, the plan inspired by traditional oriental courtyard houses allows its envelope to protect occupants from the arid climate.



Figure 41: Design strategy with Pergola in closed position by day for solar shading & retracts by night for flushing out hot air, [22].

The courtyard creates a microclimate, as shown in Fig. 42, adding a fresh and visually comfortable bubble to the indoor space with views of the vegetation. The seamless connection between the indoor areas and the courtyard allows for free air circulation and ventilates the interiors without the risk of overheating. Dynamic shading devices, such as the wooden solar pergola over the courtyard and the roller blind blackout for external openings, enable control of natural light and direct sunlight entering the indoors.

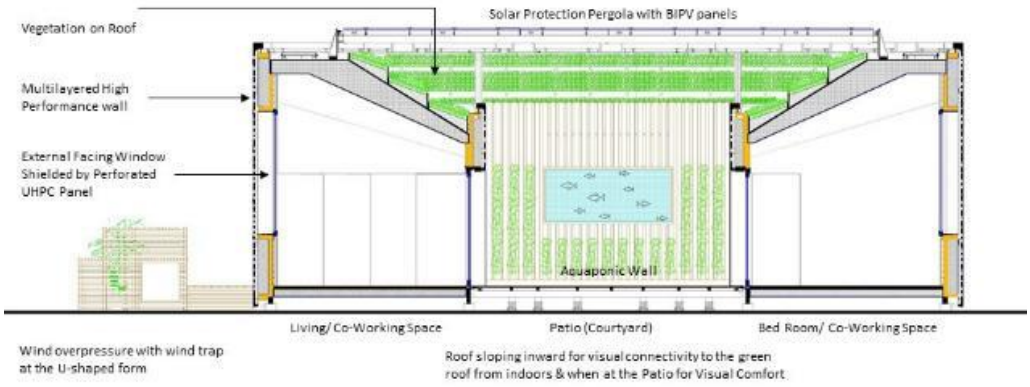


Figure 42: Sectional elevation of the BaityKool prototype showing the Aquaponic wall and architectural form with the inward sloping roof, Author.

The aquaponics wall acts as a thermal mass alongside the fish tank, improving thermal comfort and providing a visual connection for occupants from the courtyard and corridors. The vegetative wall with continuously circulating water through zip rows enables evaporative cooling at the patio and promotes natural air circulation into the corridors via the patio ventilation during favorable weather conditions.

2.3.3 The Envelop Design, Structure and Composition

To design an effective building envelope in the Middle East, particularly in semi-arid regions, the following strategies needs to be consider, some of them is the material selection and insulation. Iranfar and Al-Din [86] conducted a study in Iraq to estimate different architectural styles, vernacular, early modern, and contemporary, by calculating their U-values (thermal transmittance) to assess heat gain/loss and overall energy efficiency. The authors found that using insulation for floors and roofs can reduce energy demand. In addition, they suggested to avoid using "hollow concrete blocks" (low thermal potential of this masonry unit for responding to the regional climatic characteristics). In this situation, the strategy to design, the envelope system of the BaityKool was to use vernacular material and efficient materials. The system is composed of the core structure, which includes the base structural beams, floors, walls, and roof system. The base structural beams are made from solid wood, and the floor and roof plates are composed of solid wood and engineered wood, featuring bio-sourced thermal insulation with a low environmental impact. Wood, being lighter in weight, allows for the prefabrication of the structure, with assembly, disassembly, and transportation of the 3-dimensional assembled modular form, and the implementation of final assemblies at the site. Wood, a low-density material with air entrapped within it after seasoning, is highly resistant to heat flow, a good insulator with low thermal conductivity, and possesses thermal insulation properties. The mechanical properties, like strength and flexibility, make the material inherently suitable for the climate of the Middle East region. The bio-sourced house insulation material used at floor, walls and roof as indicated below with images in Fig. 43 has the U-values for wall, roof and floor as indicated in Table 5. (Refer to **Appendix C** for the Thermal and Optic characteristics of the elements if the envelope system)

Table 5: U-values of Walls, Roof and Floor at BaityKool prototype

Prototype	BaityKool house Envelope Thermal Characteristics (w/m² k)
Structural Wall	U= 0.12
Pitched Roof	U= 0.14
Terrace Roof	U= 0.14
Floor	U= 0.16



(a) (b) (c) (d)

Figure 43: Top (a) OUATECO © cellulose insulation for roof, (b) TEXTILAINE© recycled wool fiber insulation, (c) STEICO© Wood Fiber insulation for walls, (d) METISSE© recycled cotton cloth insulation for interior walls, [22].

- Cellulose wadding from recycled newspapers is used for the roof
- Recycled wool is used for the floor
- Wood fiber used as insulation for exterior walls
- Metisse: recycled cotton used for interior walls.

The sectional view of the BaityKool structural system as in Fig. 44 shows the layers of the building elements.

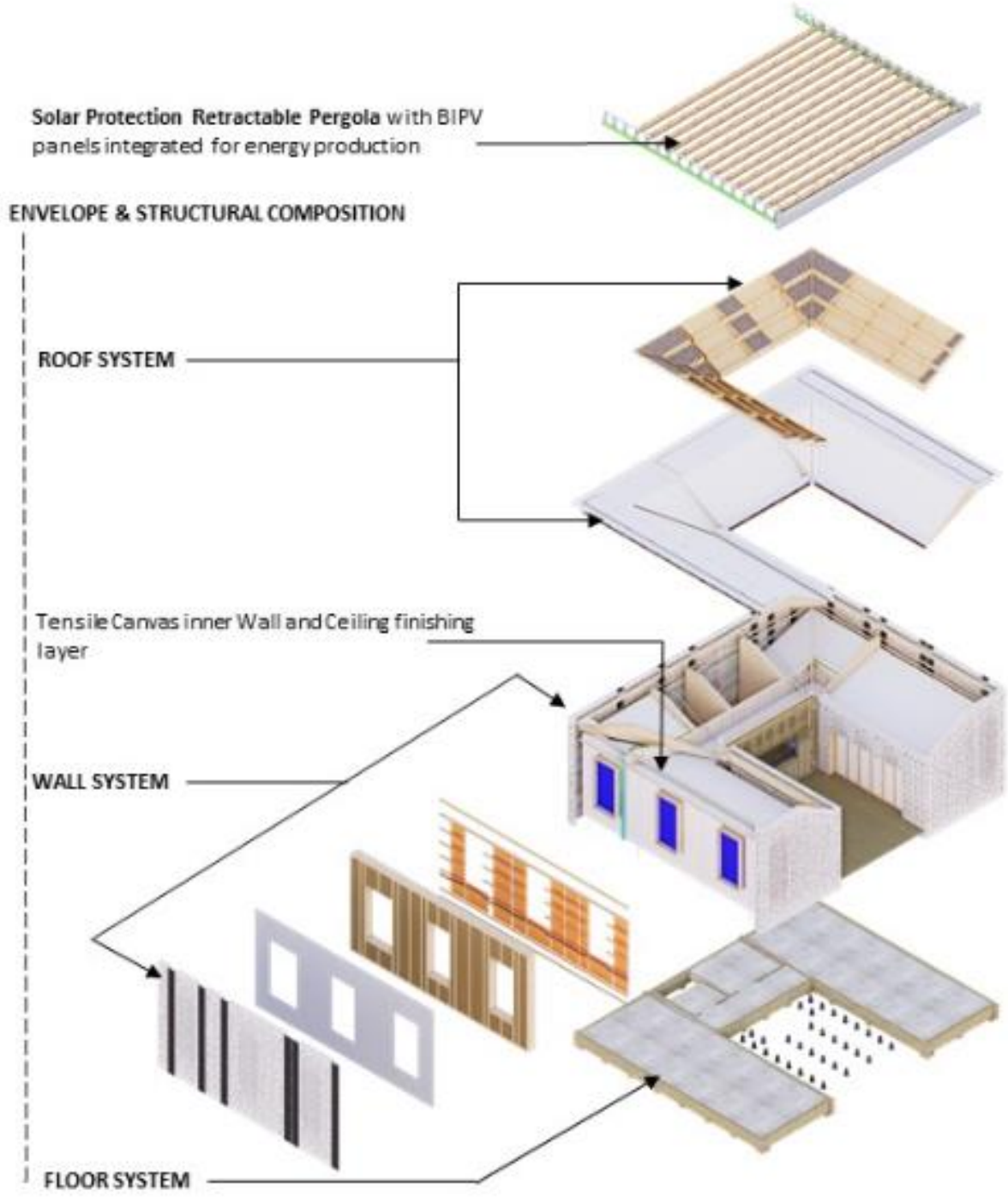


Figure 44: The sectional view of the structural system (Source: Author)

Wall System:

The wall system of the house envelope is designed with compactness as in Fig. 44, a sustainable way to save materials, control ambiance (light and solar rays), and protect from extreme external conditions. A composite multilayered wall composed of high-performance layering with the outside-to-inside layer of materials as indicated below in Fig. 45.

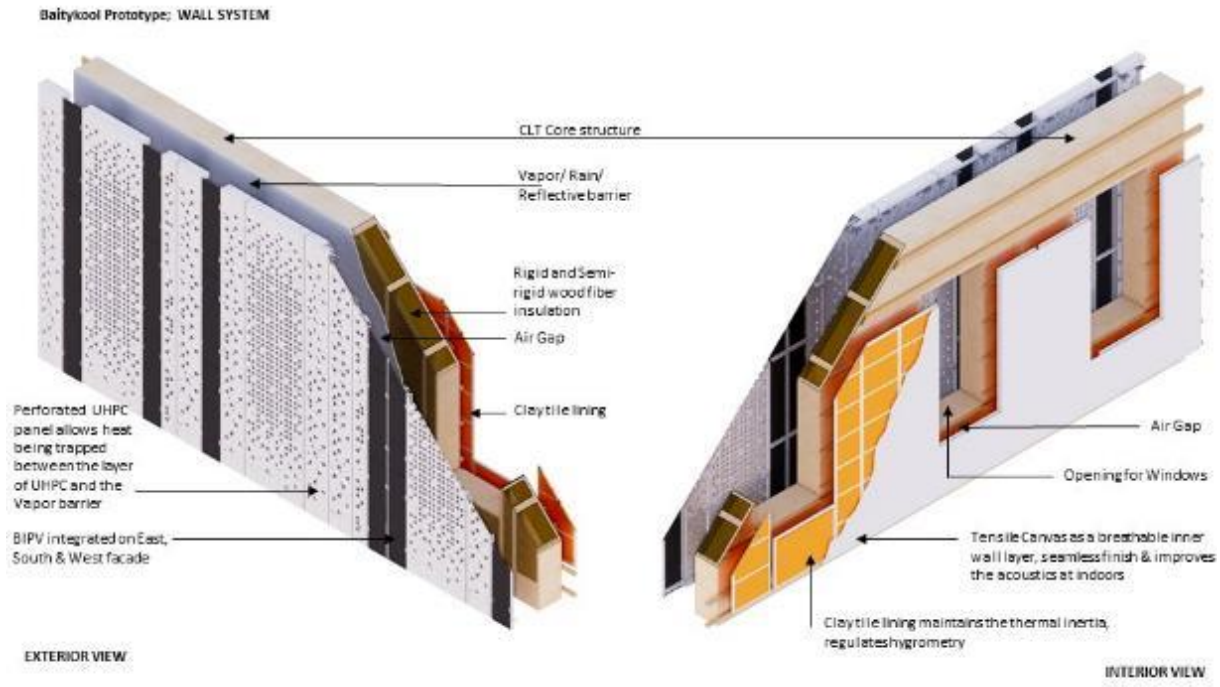


Figure 45: View of the high-performance layering wall composition, Author

- Ultra-High Performance Fiber Concrete (UHPC): a modular perforated panel façade. It is a monolithic closed mineral form explicitly developed for this project based on the idea of the 'Mashrabiya', a classical Middle Eastern architecture with a perforated wall providing comfort and privacy. The façade protects the window opening from harsh weather and sandstorms outside (details in Appendix C).
- Air Gap: This allows air circulation through the perforations and prevents heat from being trapped between the layer of UHPC and the Vapor barrier. Air acts as an insulator and prevents conductive heat transfer from the UHPC panel to the inner layer of the composite wall (details in Appendix C).

- The vapor/ Rain/ Reflective barrier protects the inner layers from water and moisture and reflects the solar rays (details in Appendix C).
- Rigid and Semi-rigid insulation with wooden stiffeners, STEICO, a component made of wood fiber with a Thermal Conductivity λ (lambda) value of 0.036 W m^{-1} K^{-1} (this is the measure of heat travel through the material through conduction); the lower the value, the better the performance (details in Appendix C).
- Structural Cross Laminated Timber (CLT) panel is the vertical structural material of the building shell. CLT panel allows higher vertical load carrying capacity when used in walls, which are much lighter with a lower environmental impact when compared with metal and concrete as structural material. It has high thermal inertia, offers good performance for seismic, fire and acoustics. Thermal conductivity of 0.13 W m^{-1} K^{-1} with insulation performance similar to air Crete block and better than concrete or brick block. The engineered timber material along with good structural properties has potential for airtight construction with robust walls and enables modular construction and allows easier implementation for onsite construction (details in Appendix C).
- Compressed mud bricks: Mud tile lining on the interior walls and the concrete floor maintains the thermal inertia, regulate energy exchanges and cooling management. The use of clay brick lining to the inner wood casing improves the insulation and regulates hygrometry for maximizing the comfort. Clay captures the water vapor released by occupants and equipment's at the house decreasing the humidity at the indoors. As temperature increase the vapor from clay tile is released decreasing the level of hygrometry (details in Appendix C).
- Acoustic Tensed canvas is the inner most layer regulating noise and keeping the wall breathable with seamless finish for large lengths and widths, light weight, very low VOC emission with Class A+ rating. The layer of air between the mud brick and canvas forms an insulation cushion. A non-toxic recyclable material allowing dry and clean installation (details in Appendix C).

The structural floor plates as in Figure 46 and roof plates as in Figure 47 made of wood and bio-sourced material and insulation.

Floor System:

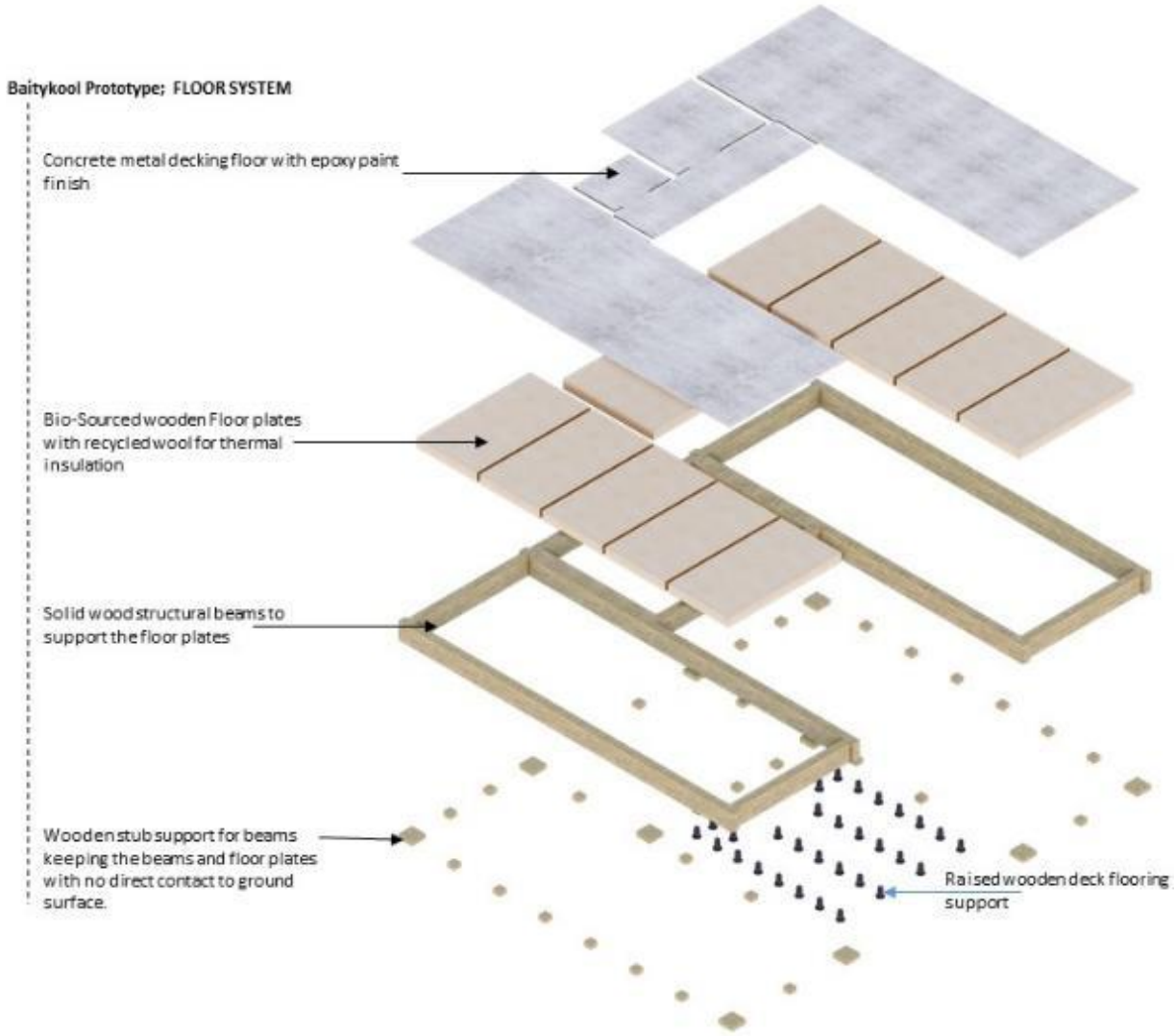


Figure 46: View of the Floor system with layering, Author.

The Floor plates are composed of solid wood structural beams supporting wooden floor plates made from solid wood and plywood with recycled wool for thermal insulation. The Floor structural beams and floor plate are not in direct contact with the ground surface. Metal decking with concrete with an epoxy-based paint finish is used as the finishing for the floor plate. The concrete allows a thermal phase shift indoors.

Roof System:

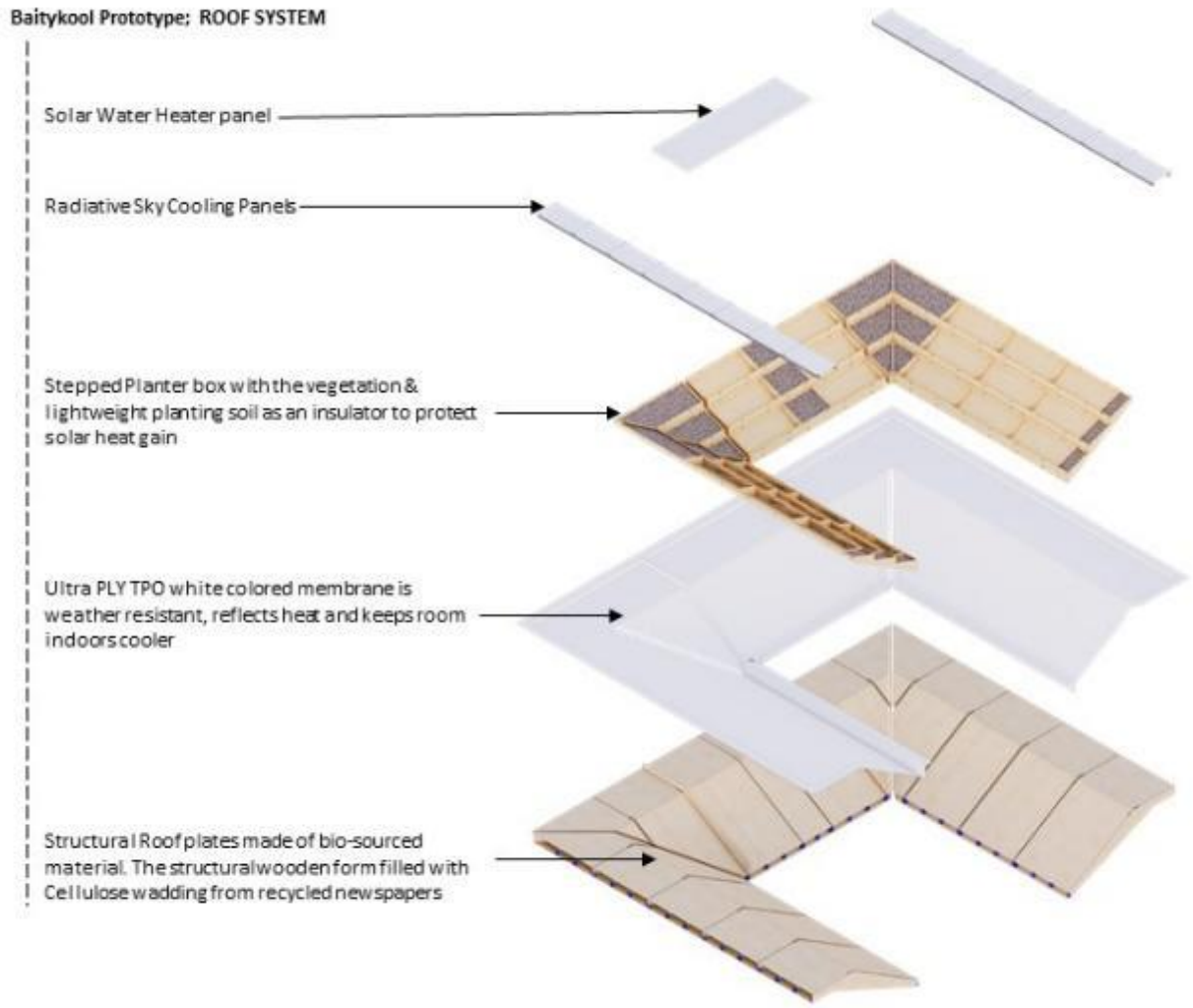


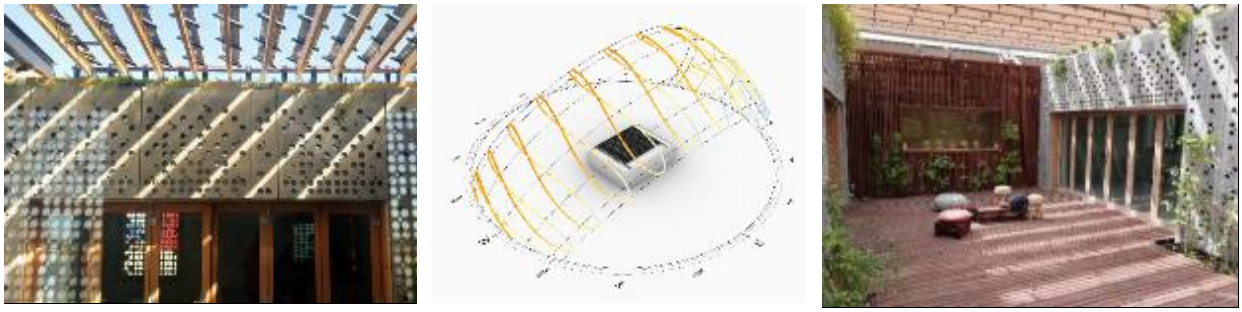
Figure 47: View of the roof system with layering, Author.

The roof plate top external surface is waterproofed with thermoplastic roofing membrane (Ultra PLY TPO), the reinforced white-colored membrane reflects light and contributes to the energy balance of the building. An environment-friendly material without chlorine, plasticizers, or halogens, easy to recycle, and has obtained ISO 14001 certification. This is compatible with green roofs and is resistant to root penetration, extreme temperatures, and tears. The roof of the prototype has innovative 'Radiative Sky Cooling' panels coupled with the cooling system. The panels reflect the solar radiation and reduce the thermal contributions from the roof. The inward sloping roof has the vegetal cover with the vegetation of a protective type based on the principle of the Oasis, with

the biodegradable wooden boxes creating stepped planting roof layers. The first outermost step is composed of plants resistant to high temperatures, and the inner steps lead to the patio with fresh and flowering plants. The roof planter boxes are filled with lightweight soil with decayed bark and peat moss, with provision of a drip irrigation mat and a drainage system built into the vegetative carpet. The smart automatic watering with the dedicated smart application monitors and manages the water consumption and uses an ecologically friendly process of filtering gray water. The presence of water and plants increases the humidity level by evapotranspiration, creating a natural cooling effect for the occupants.

2.3.4 The solar pergola as a solar protector:

The wooden beams of the patio cover incorporate photovoltaic panels at their top, acting as a sun shade during the day, as in Figure 48 (a), (c). At night, the pergola retracts to the rear south side and expels the heat from the habitat to outside with natural ventilation. The orientation of the building and solar pergola and angle of the BIPV panel are done considering the sun path as in Fig. 48 (b). The BIPV panel positioning with optimal tilt and orientation based on sun path allows maximum capture of solar radiation throughout the year and also provides sunshade preventing the overheating at patio with intense direct sunlight. Solar protection with reduced solar thermal load in the prototype is achieved with the presence of the pergola shading the patio and the roof of the prototype.



(a) (b) (c)

Figure 48: (a) View of Solar pergola from west of BK in closed position shading the patio, (b) Annual Sun path simulation for BK, (c) View of Patio shading from North of BK with solar pergola shading the Patio during 9 am, Author.

The north façade of the prototype has the wood blade claustra, which increases the visual privacy of the users of the patio (refer to Fig.40). The planters along its length allow the creeper plants to

grow on the claustra, refreshing the ambient air and reducing the dust levels. Thus, the passive choice of envelop components creates good insulation inside the house, and the hygro-thermal properties allow a suitable temperature for comfort. The aim is to reduce energy consumption for the cooling system and artificial lighting and to ensure improved thermal comfort.

2.3.5 The Natural Lighting and Ventilation Design

A healthy indoor environment with thermal comfort can be achieved with natural ventilation during moderate weather and cool nights. Good ventilation allows for the refreshing of the indoor air by pushing the hot and humid air out and drawing in cool air. Traditional architecture in the UAE used wind catchers with evaporative cooling to provide comfort indoors without using energy during the day. The wind towers provide cooling by night, flushing out stored heat from the building fabric [87].

Natural Lighting

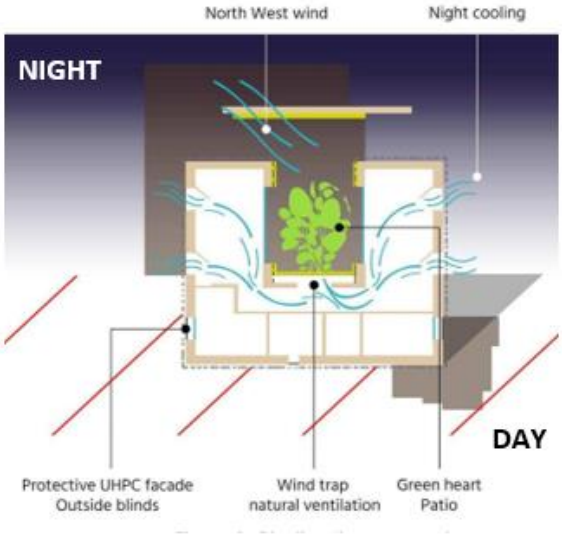
The BaityKool prototype with a U shape maximizes the benefit of natural ventilation. The glazed sliding folding doors in the living and bedroom areas, which face the patio (Courtyard), allow for natural lighting (refer to Fig. 35 (c)). The windows on the east-oriented living and west-oriented bedroom are not directly exposed to the sun; they have the UHPC perforated panels that shield the window openings, protecting from glare, direct sunlight, heat, and visual intrusion (refer to Fig. 45). The perforated façade is a reinterpretation of the traditional oriental mashrabiya in a contemporary way, adding an aesthetic identity. The indoors are light-filled spaces with playful patterns of circles and patterned shadow play on the interior walls without compromising privacy.

The UHPC perforated panel acts as a thermal regulator; the concrete façades are not directly clad to the walls. The air gap between the perforated UHPC panel and vapor barrier allows free air circulation and prevents moisture buildup in the composite wall layer at the exterior. The air acts as an effective insulation and improves the thermal performance of the building wall, reducing heat gain and cooling load. The glazed sliding folding door openings facing the courtyard are protected from the sun, and the pergola has BIPV panels as a solar canopy and solar skin. At night, the perforations, the pergola, and the wooden-bladed claustra create a lighting effect on the prototype. A play of reflective perforation created from the reflected moonlight from the vapor barrier and the lit perforation with glazing recalls the stars of the Milky Way. The windows and

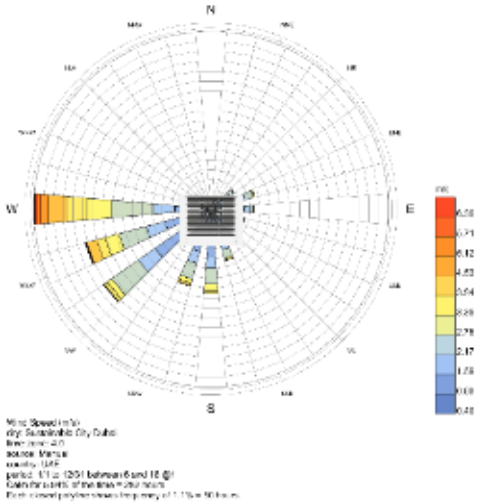
sliding folding doors also have the automated protective Roller Blind Blackout (RBB) on the exterior side of the glazing, minimizing the solar heat gain.

Natural Ventilation

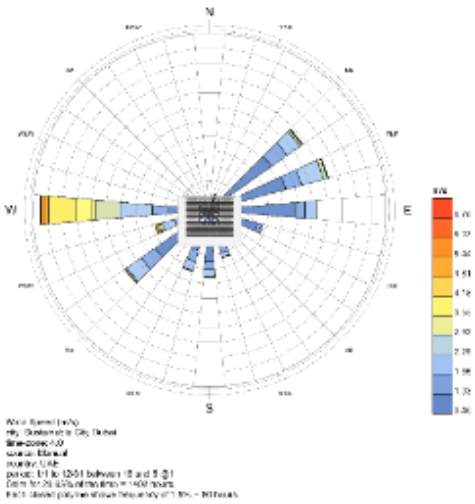
The window positioning in the living room, Kitchen, bedroom, and patio ventilator at the corridor, as indicated in Figure 48, allows cross ventilation at the prototype. Natural ventilation is used during days and nights with favorable weather conditions when the temperature outdoors is cooler.



a)



(b)



(c)

*Figure 49: (a)**:** BK natural ventilation strategy day & night, Center (b) Wind rose annual during day, (c) Wind rose annual during night. (Source: Left image BK Manual, Center & right image by Author.*

The night ventilation strategy extracts heat from indoor rooms, quickly refreshing the internal wall materials. The home automation system controls the opening and closing of the windows and the protective blinds for solar rays based on the occupants' visual and thermal comfort conditions.

There is a patio ventilator in the corridor area on the aquaphonic wall, allowing air circulation from the central area of the prototype and cross-ventilating the interiors. The patio ventilator on the exterior side has zip rows with dripping water and vegetation filtering the dust in the air and reducing the radiant temperature, improving the thermal comfort of the interiors with natural ventilation.

2.3.6 The vegetative system at the roof and green core patio

Vegetative Roof

The roof design maximizes the green roof area, sloping inwards in steps towards the courtyard on the three sides, allowing better air movement, and a pleasant visual connection is achieved between the user and the vegetation, as indicated in Fig. 50 (d). Also builds the capability to collect rainwater through the sloped surface.

Green Core Patio

The Patio (courtyard) opens on the north side, allowing the night wind, and the closed south side protects the patio from the sun, as in Fig. 49 (a). The Fig. 50 (a) and (b) shows the BaityKool during the SDME 2018 competition period, and the Fig. 50 (c) and (d) shows the BK living lab during 2022-2024 at TSC. The presence of water and plants in the patio increases the level of humidity by evapotranspiration giving an impression of natural cooling to the occupants.

The south face of the courtyard has an aquaponics system that allows natural food production with the integration of a fish tank and vertical vegetative zip rows in the building architecture, as shown in Figure 50 (d). The innovative system combines aquaculture and agriculture, creating a fresh atmosphere in the house. In addition, there is a saving of water by using bio-filtered grey water from the house. The courtyard features a light and heat control system that incorporates both passive and semi-passive solutions, allowing occupants and plants to thrive. The courtyard design

maintains the floor area ratio to the building shape to reduce surfaces exposed to external temperature. The biodiversity on the vegetation at the roof and the green core courtyard, along with the ventilation strategy, creates energy-efficient and enhanced comfort indoors.



(a)



(b)



(c)



(d)

Figure 50: (a) View of the Green patio at the BK prototype during the SDME 2018 Competition phase, (b) View of the aquaponics system with the aquarium & vegetative wall seen from the Patio. (c) View of the vegetative claustra wall at the BK prototype facing the North, (d) View of the green patio & vegetative roof at the BK living-lab at TSC, (Source: top image BK manual, bottom image by Author

Integrating vegetation at the roof, patio and claustra, along with the innovative compact composite multilayered envelop system, helps improve thermal comfort indoors and reduce the cooling load. The natural lighting, along with user-controlled automated roller blind shading for windows, enables control of ambient light quality, suiting the occupant's activity. The HVAC uses the innovative radiative sky cooling system to minimize energy consumption. The building's

integrated photovoltaic (BIPV) panels, located on the pergola and integrated with the east, west, and south façades, enable energy production. Wastewater treatment with Lombrifiltration, bio-solar-purification, and food production with aquaponics adds to a sustainable lifestyle. The house works on the principle of optimizing solar energy production while minimizing all consumption by using passive and semi-passive solutions, along with using all appliances with a minimum energy class 'A', which, when working, consumes the minimum energy. The intelligent management with home automation integrates all data and controls on a single monitor for plotting and supervision. This increases the energy efficiency and its management to generate an energy balance.

2.4 Role of BaityKool Lab as an experimental tool

The BaityKool prototype, designed as a bioclimatic architecture for extreme warm climates, offers an opportunity to gain valuable insights into the practical application of its principles and innovations. The solutions, tailor-made for the extreme warm climate, culture, and geographic context, highlight the importance of local building adaptation with the potential to integrate traditional and modern techniques. The prototype serves as a living lab, creating potential to explore various experiments that test the effectiveness of design strategies, materials, and systems in extreme warm climatic conditions.

2.4.1 Simulation Analysis and Discussion at Design Phase

A French dynamic simulation software Archiwizard, was used to analyze natural light, real-time cooling needs, and energy balance, utilizing weather data from Dubai, as well as wall, floor, and roof composition and occupancy scenarios. The goal of the modeling and simulation is to find the best architectural design solution for natural lighting and thermal comfort conditions with reduced energy consumption.

The climate data and weather analysis from the (epw file) from the SDME contest shows the coldest temperature of 9 °C in winter in January and the hottest temperature of 48 °C in June to August. The analysis revealed that the months from November to March presented an opportunity for Night and natural Ventilation. The high inertial material showed possibilities to cool the prototype maximally during the night and maintain coolness during the day.

An energy balance forecast was created using results for night cooling and passive strategies as indicated below.

- Increase the house's inertia to allow thermal dephasing, enabling the exterior heat waves to be released during the night.
- Natural night ventilation is used to evacuate the heat during the night.

The house envelope system is composed of bio-sourced materials with thermal and optic characteristics. A comparison of the BaityKool house with another Eco House in Oman with a similar climate condition as in Table 6 shows measures considered for BaityKool.

Table 6: Comparison between Eco house Oman and BaityKool for thermal performance, [22]

Prototype	Eco house Contest Winner- Oman	BaityKool
Structural wall	U=0.13	U=0.12
Pitched roof	U=0.13	U=0.14
Terrace roof	U=0.13	U=0.14
Floor	U=0.17	U=0.16

Passive strategies used after the simulation studies:

- North Orientation, to protect the house from sun
- None of the windows directly exposed to sun (Windows designed with protection from perforated UHPC panel).
- Northwest winds to have natural ventilation
- Patio design, to have a private garden cool down by plants evapotranspiration and shade from the solar canopy (PV- Pergola)

The simulation test demonstrated the potential of night cooling with natural ventilation in November and March, resulting in reduced HVAC system use and energy savings. Additionally, materials with high thermal inertia effectively cooled the indoors naturally at night and maintained a cool space during the day.

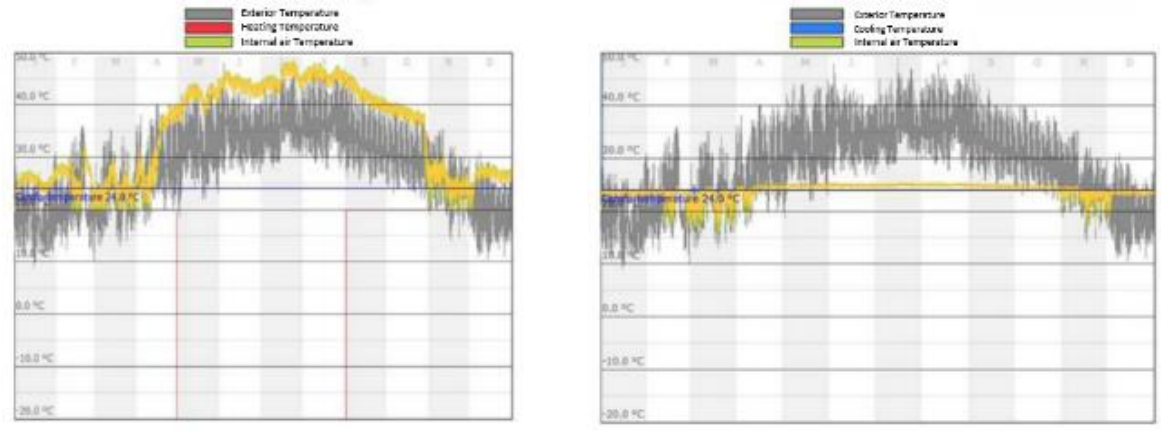
Energy Efficiency measures taken to improve house performance:

- structural and insulation design to avoid thermal bridges
- Home automated shading blinds and light dimming to control the balance between artificial lighting and natural lighting

- Home Automated Night Ventilation
- Use of clay tiles lining in the interior wall layer to increase the inertia
- Use of equipment with high energy class

HVAC simulation of the house was conducted using natural ventilation without air conditioning to determine the thermal needs and predict indoor temperatures and cooling loads through passive strategies. The annual report for the simulation during the competition period provides a basis for developing strategies with the prototype at an average of 25°C. Using a bioclimatic approach, the results showed a reduction in electric consumption for cooling. The electrical energy simulation on the System Advisor Model (SAM) balance report for the competition period from 11/18 to 11/27 indicated that the total energy produced by the PV system matched the daily energy consumption during the 10 days of the contest. The prediction also showed potential energy balance throughout the year.

House performance annual simulation comparison between the passive analysis on house performance using only ventilation (without AC) and the active analysis simulation with use of HVAC equipment is as in Figure 51 (a) and (b). This is to determine the thermal requirements and predict the indoor temperatures and cooling loads using only passive strategies and to predict the AC energy demand with (T_{INT} = 24 °C).



(a) (b)

Figure 51: Comparison of BaityKool house performance annual simulation at the design stage between (a) passive analysis without AC, (b) with HVAC equipment, [22].

The comparison shows the prototype with an average on the middle temperature, without HVAC an optimal comfort indoor temperature of 25 °C cannot be achieved. The cooling load is a minimum of 4W and maximum 20W as in Fig. 52.

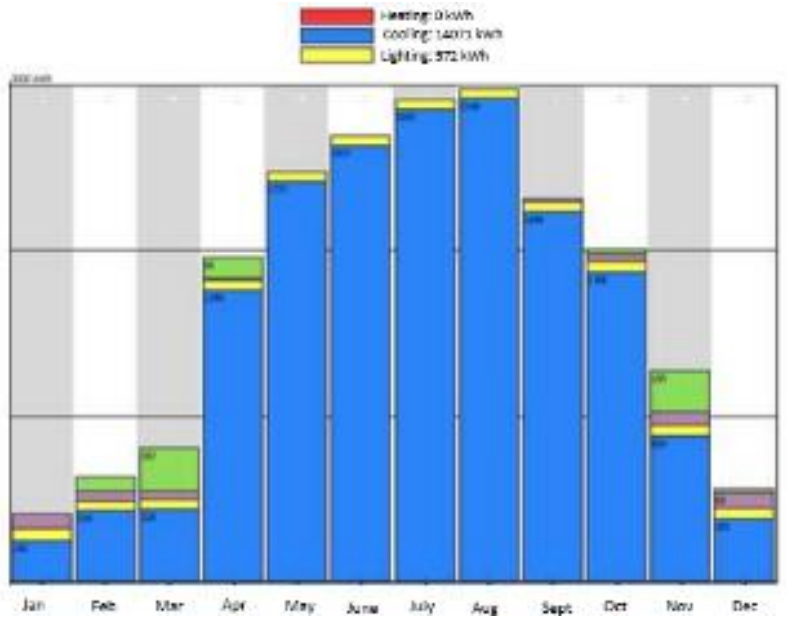


Figure 52: Electrical consumption with use of HVAV system combined with passive strategies from November to March, [22].

Electrical Energy Balance

Considering Dubai as the location for the BaityKool prototype with high solar radiation, innovative PV to produce electrical energy for the house equipment. Software System Advisor Model (SAM) predicted the environmental benefits with the photovoltaic program as in the task in 10 (refer project manual [22]. The annual energy simulation PV system which include the solar pergola, east, west and south façade, the energy yield depending on orientation was

• Roof	9537.77 kWh/year	1703 kWh/kWp
• East Façade	1994.90 kWh/year	1385 kWh/kWp
• West Façade	1049 .00 kWh/year	728 kWh/kWp
• South Façade	1441.00 kWh/year	1001 kWh/kWp

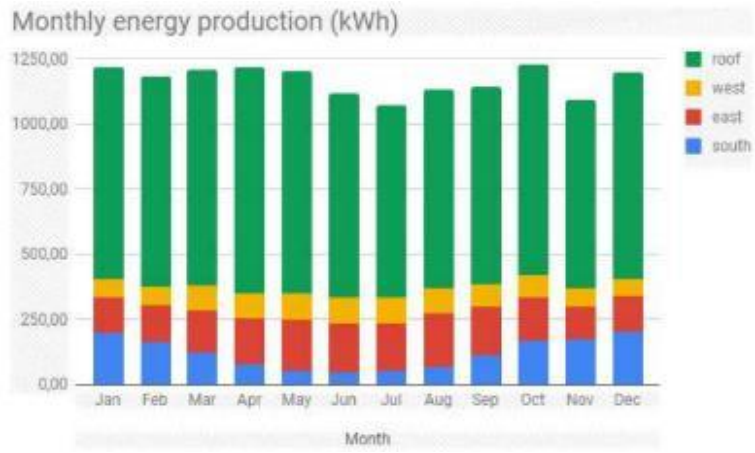


Figure 53: Monthly predicted energy production by PV modules, [22].

The solar pergola PV modules produce about 70% of the energy and 30% by the east, west and south façade PV modules. The maximum PV production predicted in simulation study during the year is 7.34 kW. The SDME 2018 guidelines had a maximal AC load below 8kW over the year. The montlty predicted energy production by PV modules is as indicated in Fig. 53.

2.4.2 Performance results of BaityKool at SDME 2018 Competition phase

The first edition of the SDME focused on Sustainable development, with the UAE government establishing initiatives to improve building energy efficiency. The aim is to accelerate the building efficiency policies and programs, working towards the Zero Energy Building goal by 2030.

Table 7: Sustainability contest evaluation criteria at SDME 2018, [19]

Sr. No	Criteria	Description
1	Sustainability and the project concept	Relationship between the general concepts of the house and sustainability, assessing the team's understanding of the sustainable built environment and how this understanding is incorporated into their project
2	Construction system	Sustainability merits of the selected system, considering aspects such as water use, solid waste, recyclability, and health and safety.
3	Materials	Sourcing and the environmental impact of selected material, also considering their content and possibilities for reuse or recycling, embodied energy, durability, and maintenance requirements.
4	Bioclimatic strategies	Application of passive design strategies to maintain a healthy and comfortable indoor environment, minimizing energy requirements.

5	Active systems	Selection of equipment, HVAC, and lighting systems that effectively maintain a healthy, functional, and comfortable indoor environment while minimizing environmental impact
6	Solar systems	Evaluation of the thermal solar, PV, and energy storage systems, including their environmental benefits and impacts, as well as their energy recovery time, CO2 emission reduction, and durability
7	Water	House and landscaping water conservation strategies, including low-flow or water-saving fixtures, high-efficiency irrigation solutions, greywater systems, water treatment, and water reuse.
8	Vegetation	Use of native and low-water-use locally adapted plants and low maintenance solutions as well as the use of plants, green walls, or roofs, to reduce the surrounding heat and the house energy demand.
9	Waste	Waste reduction, collection, and management, as well as its reuse or recycling possibilities during the project's construction, use, and end-of-life phase.

The SDME was challenged to design, construct, and test sustainable solar houses that responded to the local climate of the UAE. BaityKool was one of the eleven houses designed and built at the SDME 2018 competition with a floor area of 105.5 m². The U-shaped house is closed to the harsh exterior and open to the sheltered courtyard. Timber was the most commonly used material, with 64% of the teams utilizing it as a primary structural material due to its lightweight nature, flexibility, high thermal performance, fast installation, good seismic and acoustic performance, and environmental advantages.

The SDME evaluation, conducted by three international experts, assessed the degree of sustainability based on the criteria outlined in Table 7.

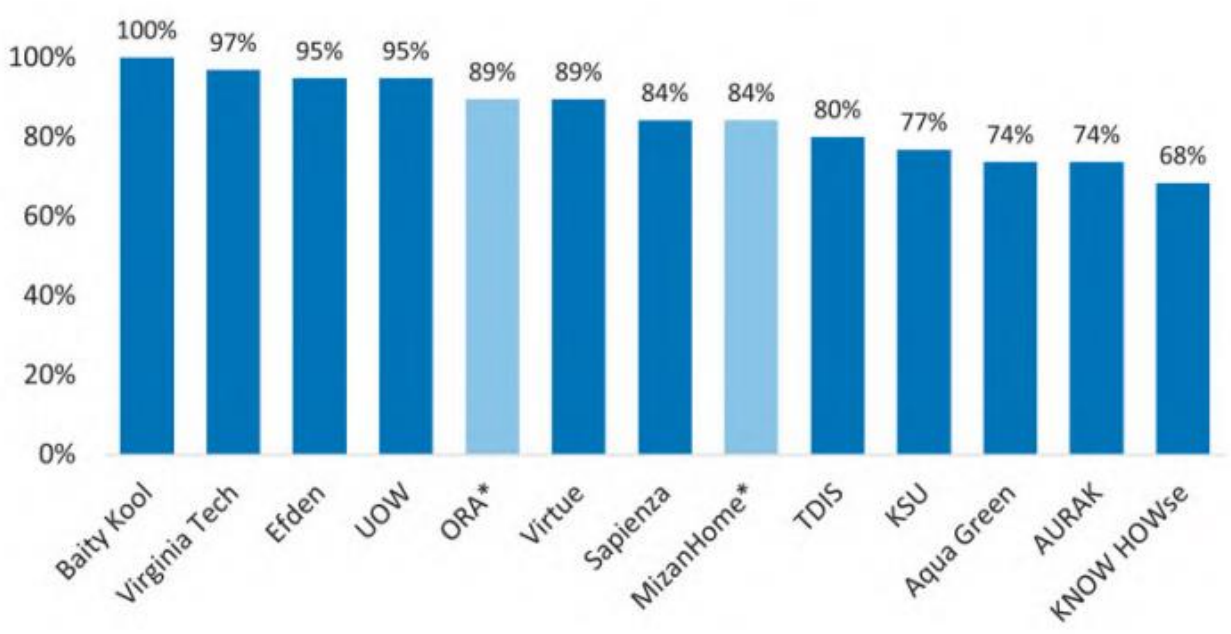


Figure 54: Sustainability score and ranking of SDME 2018 competition houses based on Alshikh et al, [19].

BaityKool was ranked 100%, as indicated in Figure 54, according to the results published on the SDME 2018 competition website. The research further analyzed this for the benefits of off-site construction, adding to sustainability. Considerations in design taken by participating teams include the use of materials with low embodied energy, the implementation of passive design strategies, the selection of high-efficiency appliances and systems, the use of environmentally friendly refrigerants, and the integration of solar technology. Contemporary designs developed for the prototype were adapted to the climate and respected the culture of the Middle East region, with reinterpretation of the valuable aspects of vernacular architecture.

A comparative study of SDME 2018 competition houses was conducted with two Nearly Zero-Energy early adopters in the UAE: The Sustainable City Villa, The Masdar City Eco-Villa & the Dubai Green Building regulation, specifically Al Sa'fat, as applicable in 2017. This comparison showed the thermal performance aspects of the BaityKool envelope along with the SDME 2018 houses and the adaptor case study projects, as indicated in Table 6. The envelope's thermal performance is a crucial aspect responsible for energy consumption and associated carbon emissions.

The details of the two Nearly Zero Energy early adopters in UAE: The Sustainable City Villa, The Masdar City Eco-Villa & the Dubai Green Building regulation: Al Sa'fat's indicated below:

The Sustainable City (TSC)

Conceived as a low-carbon residential and mixed community in Dubai with 500 villas, 89 apartments, and facilities like a school, Mosque, recreational facility, and urban farm. The Villas incorporate passive strategies and highly efficient systems with solar power meeting 40% of the energy demands. The case study considered the largest four-bedroom villa, consuming about 100 kWh/m^2 per year, a 65% lower consumption than similar villas in the UAE.

The Eco-Villa Masdar

A highly energy-efficient residence designed to meet the Emirati Family's needs, the house is constructed using insulated concrete foam (ICF), high-energy equipment, and energy management systems to maintain consumption below 97 kWh/m2 per year. The house is powered by a PV system generating about 102% of the energy demand.

Dubai Green Building Regulations: Al Sa'fat

Issued by Dubai Municipality in 2010, the first phase of the application was mandatory for all government buildings. In 2020, Dubai Green Building Regulations were replaced by Dubai Green Building System, which is compulsory to apply to all new buildings getting a Silver Sa'fa and owners achieving high performance, Gold, and Platinum Sa'fa. Al Sa'Fat ensures a sustainable environment for future generations, aiming at improving building performance, reducing energy consumption by at least 30%, increasing the efficiency of electrical and mechanical systems, and reducing the carbon footprint. The new regulation in 2023 has no change in the thermal envelope transmittance requirements, U-values of walls, glazing, floors and roofs. The heat transfer coefficient for the roof is 0.3 w/m^2 k for Silver, Gold, and Platinum Sa'afa, external walls, and exposed floor is 0.57 w/m^2 k for Silver Sa'afa and 0.42 w/m^2 k for Gold and Platinum Sa'afa. [17].

Table 8: Comparison of thermal envelope of SDME 2018 houses with two nearly net-zero early adopter houses in UAE & Dubai Green Building Regulations, Al Sa'fat. [19].

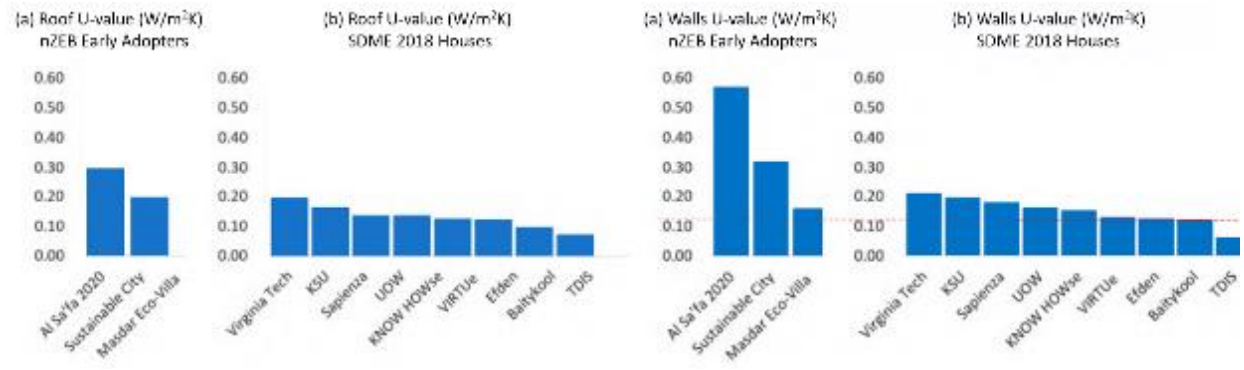
	U-Value (w/(m^2 k))					
	Name	Opaque			Transparency	SHGC
		Wall	Roof	Floor		
Dubai Green Building Regulation	Al Sa'fat	0.570	0.300	-	2.100/1.900	0.350/0.290/0.220
Sustainable nZEB	The Sustainable City	0.320	0.200	1.300	1.300	-
Early Adoptor	Masdar City Eco-Villa	0.160	-	-	-	-
SDME 2018	Viginia Tech	0.210	0.100	0.140	-	-
	KNOW HOWse	0.153	0.169	0.309	1.666	0.450
	KSU	0.195/ 0.192	-	-	1.533	0.270
	Sapienza	0.180	0.130	0.280	1.000	-
	UOW	0.161	0.200/0.164 [b]	0.163	1.400	-
	Virtue	0.133/ 0.127[a]	0.127	0.131	-	-
	Efden	0.126/ 0.133	0.126	0.193	1	0.280
	BaityKool	0.120	0.140	0.160	-	-
	TDIS	0.060	0.075	0.072	-	-

[a]U-value of tilted roof = 0.200 (w/m² k), flat roof = 0.164 (w/m² k). [b]U-value of north wall = 0.133 (w/m² k), east west south walls = 0.127 (w/m² k).

The Fig. 55 (b) and Table 8 indicate the U-value for BaityKool exterior wall is 0.12 w/m² k , which is 78% lower than the Al Sa'fat silver rating (0.57 w/m² k), 60% lower than TSC Villa (0.3 w/m²

k and 25% lower than Masdar Eco-Villa (0.16 w/m² k). The U-Value of the roof, as in Fig. 55 (a) and Table 2.3, shows 0.14 w/m² k , which is 53% lower than the Al Sa'fat standard for roof 0.3 w/m² k , 30% lower than the TSC Villa (0.2 w/m² k).

U-value comparison for exterior walls & roof:



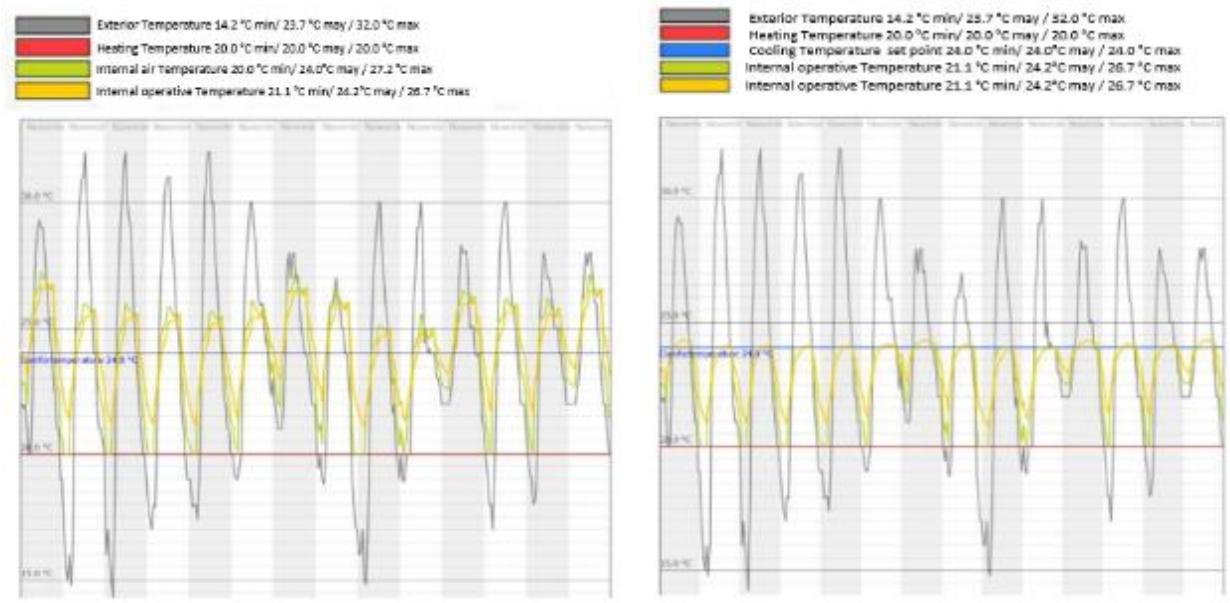
(a) (b)

Figure 55: Comparison of SDME 2018 houses with two nearly net-zero early adopter houses in UAE & Dubai Green Building Regulations, Al Sa'fat. (a) Roof U-value, (b) Wall U-value, [19].

The thermal performance at BaityKool was achieved through shading by the PV and the roof with vegetation, as well as the use of an ultra-Ply white TPO lining layer on roofs to protect against solar radiation and reduce overheating. The floor at BaityKool with a solar shading pergola achieved a lower U-value of 0.16 w/m² k, 72% lower than the Al Sa'fat standard limits. At BaityKool, the protection of the windows with the architectural element, the perforated UHPC panel on east and west orientation, and a low window-to-wall ratio led to a low Heat Gain Coefficient (SHGC). This is also achieved by double glazing with solar control glass and protecting the glazing from direct solar radiation

The envelope's thermal performance at BaityKool exceeds the requirements of Al Sa'fat standards for Minimum Building Envelope Performance Requirements and for better values than the two high-performing comparison case villas. The prototype, with its envelope system design, ventilated façade, window orientation, exterior and interior motorized shading devices, and quality insulation on walls, floors, and roof, enhanced the potential for better energy performance.

BaityKool house performance during the 10-day SDME 2018 contest period in November is compared between the 'Passive analysis' and 'Active analysis' as indicated in Fig. 56. It reveals that the bioclimatic strategy, combined with the high-performing HVAC system featuring optimized window surfaces and well-balanced insulation design, could significantly reduce electricity consumption for cooling needs in November.



(a) (b)

Figure 56: (a) Passive analysis, (b) Active analysis (daily results/ general results), [22]

The electrical consumption during the 10-day competition period in November is indicated in the electrical load schedule Table 9.

Table 9: Electrical consumption load schedule during the 10 days SDME 2018 competition period in November

HVAC	HVAC	66021
Appliance during the contest period	Lighting	19855
	Refrigerator + Freezer	6632
	Washing Machine	6650
	Drying Machine	6650

	Oven	22220
	Home electronics	11290
	Charging Car	52760
Systems	Systems	305
Total (Wh)		**205193**

The 10-day SDME 2018 contest PV simulation shows maximum output of 6.77kW, a total energy produced by PV system was 365 kWh. The energy balance as in Table 10 indicates PV production could produce as much energy needed by the electrical load during the year and the 10-days competition. The PV modules are connected to the battery by an MPPT charger, then connected to the inverters, which supply electricity to the loads, and the surplus energy is injected into the grid. The PV solution could demonstrate the ability to produce enough energy during the period of completion.

Table 10: Energy balance comparison for energy production and energy consumption between annual prediction during the design phase and the 10-day SDME 2018 competition period.

	Energy production (kWh)	**Energy consumption** (kWh)	**Energy Balance** (kWh)
Annual Prediction	14023	8954	5069
10-days of SDME 2018 competition period	**338**	**204.4**	**133.6**

The SDME 2018 jury report commented on the performance of the BaityKool prototype during the 10-day test of the contest in November. The engineering and construction of Baitykool integrated the approaches of architecture and cooling strategies, resulting in the lowest installed capacity of air conditioning. The innovative strategies of the high-performance UHPC wall with the CLT coupled with the perforated solar shading cladding to obtain a breathing wall. The motorized PV (solar) pergola enabled improved thermal performance, providing cool radiant comfort temperatures throughout the courtyard and interiors, with the integration of natural ventilation. The architecture concept with the courtyard appreciated for its suitability to the Middle East context. The potential of the passive strategies recognized with the thermally comfortable exterior and interior spaces. The crafted design detail integrating technology with material and devices for the enhanced house performance. The energy efficiency features the radiative sky

cooling, the thermal storage capacity of the wall composition, automated building elements for allowing natural ventilation. The envelope system with the ventilated façade with the reflective element. The integration of BIPV panel in an aesthetic way in to the building and the movable PV solar pergola shading the roof and patio. The innovation of the vertical garden using the closed water eco-system. The BaityKool prototype could achieve awards for the high performance achieved at the contest. (refer Fig. 15 (a) and (b)) making a need to analyze for its performance across the year during the seasons of the extreme warm climate.

2.4.3 Need for Experiment at Living Lab post SDME competition

The first level of validation for the prototype design tailored to the warm climate of the UAE was achieved with the results and awards received at the SDME 2018 contests. BaityKool prototype performed positively at the Sustainability, Energy Efficiency, Architecture, Innovation, Energy Management, and Engineering and Construction contests. The constitution of the BK-Lab extension in the United Arab Emirates (UAE) post SDME 2018 for research & development led to opportunities to test and experiment with the prototype for the climatic seasons across the year. With its extremely hot and arid climate, the UAE has the highest energy consumption in buildings linked to mechanical systems to maintain a comfortable indoor environment. With the expansions in the construction sector, a strong focus is laid by the Government on sustainable development and initiatives to improve building efficiency and revise energy conservation codes, progressively working towards a Nearly Zero Energy Building. Alshikh et al. [18] indicate that the first and most cost-effective step to achieve high energy performance in a building is to apply passive design strategies, starting with the proper design of the building's thermal envelope. This would enhance the building's energy efficiency and reduce the need for renewable energy sources to meet its energy demands. The Government and private sectors are moving towards a zero-carbon vision. Dubai is committed to the Building Efficiency Accelerator (BEA) to improve the global energy efficiency improvement rate by 2030. The UAE started to develop early adopters of sustainable, nearly-zero projects for residences, offices, schools, and universities. The two examples of residential early adopters: The Sustainable City Dubai (TSC), the Masdar City Eco-Villa Abu Dhabi, and the two editions of SDME 2018 and SDME 2021 are initiatives towards sustainable development. The case studies of the SDME 2018 sustainable houses, to explore off-site construction and hybrid systems, showcased the characteristics and performance, surpassing the Dubai Green Building regulation, and the examples of early adopter houses. Thus, the BaityKool

Lab at TSC serves as a valuable experimental tool, enabling experiments to test the prototype's performance in response to bioclimatic strategies and architecture designed for the building in Dubai's extremely warm climate, UAE. Experimentation on thermal comfort achieved with bioclimatic architecture at the BK prototype using architectural actions for solar shading and natural night ventilation to analyze the building's energy efficiency potential.

2.5 Chapter Summary

Chapter 2 presents the BaityKool project as a full-scale, bioclimatic architectural prototype designed to test the passive design strategies identified in Chapter 1 under the extreme warm climate of Dubai. Initially implemented for the SDME 2018, where it scored 100% in sustainability, BaityKool integrates principles such as thermal mass, evaporative cooling, and solar shading through a compact U-shaped layout centered around a vegetated courtyard. Simulations using Archiwizard and SAM confirmed the effectiveness of high-inertia materials and natural night ventilation in reducing cooling loads, particularly during transitional seasons. The envelope's performance surpassed UAE standards, with wall U-values of 0.12 W m^{-2} K^{-1} and roof values of 0.14 W m^{-2} K^{-1}**,** outperforming local benchmarks by over 50%. A dynamic solar pergola with BIPV panels, automated BMS-controlled openings, and vegetative layers contribute to climate responsiveness and comfort. Comparative analysis showed that BaityKool exceeded the performance of regional nearly net-zero housing, including the Sustainable City Villa and Masdar Eco-Villa. Since 2021, its integration into The Sustainable City as a Living Lab has enabled continuous experimentation, validating the effectiveness of bioclimatic design strategies in real-world contexts. This chapter thus demonstrates how theory-informed design can achieve measurable environmental and comfort benefits in arid climates.

Quick summary of Chapter 2

- BaityKool was designed as a self-sustaining, eco-responsive habitat tailored to the extreme warm climate of the UAE, using passive design strategies like shading, ventilation, and thermal mass to optimize thermal comfort and minimize energy consumption.
- Post-SDME 2018, the prototype became a Living Lab in Dubai’s Sustainable City, serving as a real-life platform to test bioclimatic solutions, smart building systems, and renewable energy integration year-round.

- The U-shaped layout centers around a green courtyard, allowing for privacy, passive cooling, natural light, and transformation between co-living and co-working modes.
- The envelope includes multi-layered composite walls with materials like CLT, UHPC, and recycled insulation (wool, wood fiber, cotton), achieving superior thermal performance well beyond local building code standards.
- A sloped green roof and integrated aquaponics in the courtyard enhance biodiversity, regulate microclimate, and support food and water sustainability through greywater recycling.
- BaityKool excelled in SDME 2018, ranking top in sustainability contests and surpassing Dubai's green building codes, making it a benchmark for future nearly zero-energy buildings in hot climates.

Chapter 3.

Experimental scenarios and protocols

Chapter 3. Experimental scenarios and protocols

3.1 Introduction

This chapter provides an overview of the experimental design, scenario, protocol, instruments, tools, measurement parameters, and data analysis procedure. The experiments on thermal comfort were conducted at the BaityKool Prototype during the winter, peak summer, and transitional seasons in Dubai, United Arab Emirates. The experiments on solar shading and natural ventilation were designed to evaluate the performance of the envelope system and the potential of natural ventilation to cool indoor spaces effectively. The experiment on the patio environment tests the courtyard-based design for the extremely warm climate to analyze its benefits and the response of architectural form and bioclimatic design strategies. The BK prototype's performance was assessed using a passive approach to determine its potential to enhance thermal comfort conditions in buildings in an extremely warm climate while reducing energy demand for air conditioning. The experiments are conducted across two seasons and two transitional periods under various scenarios involving architectural actions such as solar shading and night ventilation. The need to evaluate the prototype arose from the positive results obtained during the SDME 2018 Sustainability contest, a 14-day testing phase held in November 2018. The experiments proposed in this chapter play a crucial role in testing the prototype's hypothesis across all seasons in Dubai, UAE. The results and analysis from the experiments help address the bioclimatic research questions and validate the family dwelling model designed for the extremely warm climate in terms of its performance and benefits. The prototype, functioning as a living lab at The Sustainable City Dubai, enables the assessment of thermal comfort through passive strategies to achieve an energy balance and develop suitable bioclimatic management for buildings in an extremely warm climate. The findings from the experiments and their analysis confirm the importance of properly and intelligently managing the building's operation following seasonal changes and comfort needs.

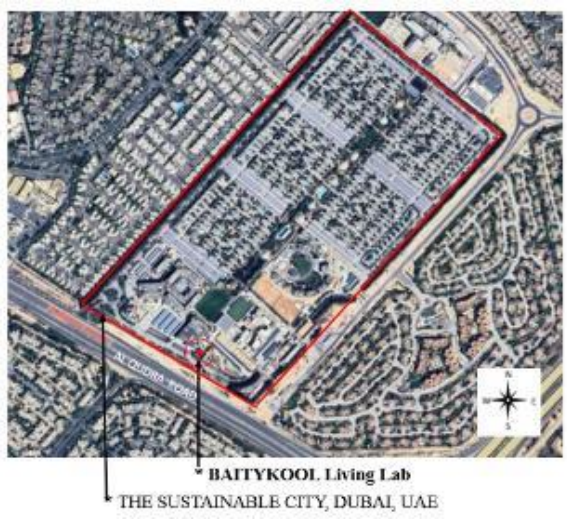
3.2 The experimental zone

The experimental zones at the BaityKool prototype, designed for the extremely warm climate of the UAE, located at TSC, Dubai, UAE. Fig, 57 (a) shows the map of Dubai indicating the location of TSC at the southern sector of Dubai at the edge of the desert approximately 30 to 35 kilometers from the coastline of Dubai. Fig. 57 (b) shows the map of TSC with the location of the BaityKool living lab. Fig. 58 (a) shows the BaityKool living lab with the site context of the neighboring SEE Institute on the west and the sustainable homes on the east. The BaityKool living lab includes the

living room, kitchen, bedroom, and patio, as shown in Fig. 58 (b). The East-facing living room measures 3.4 × 7 m, with a volume of 68.62 m^3. The kitchen measures 3.4 × 2.2 m, with a volume of 7.5 m^3. The West-facing bedroom measures 3.4 × 5.8 m, with a volume of 54.7 m^3, as shown in Fig. 59 (a). The ceilings of the living room and the bedroom, shown in Figure 59 (a) & (b), slope on one side with a varying room height of 3.3 m on one side and 2.3 m on the other. The corridor connects the living room and kitchen, measuring 2.3 m in height and with a volume of 21.5 m^3.



(a)



(b)

Figure 57: a)Map of Dubai, UAE showing location of TSC, b) Map of TSC, Dubai showing BK Lab, (Source: Google Earth accessed on 5th Sept. 2025).

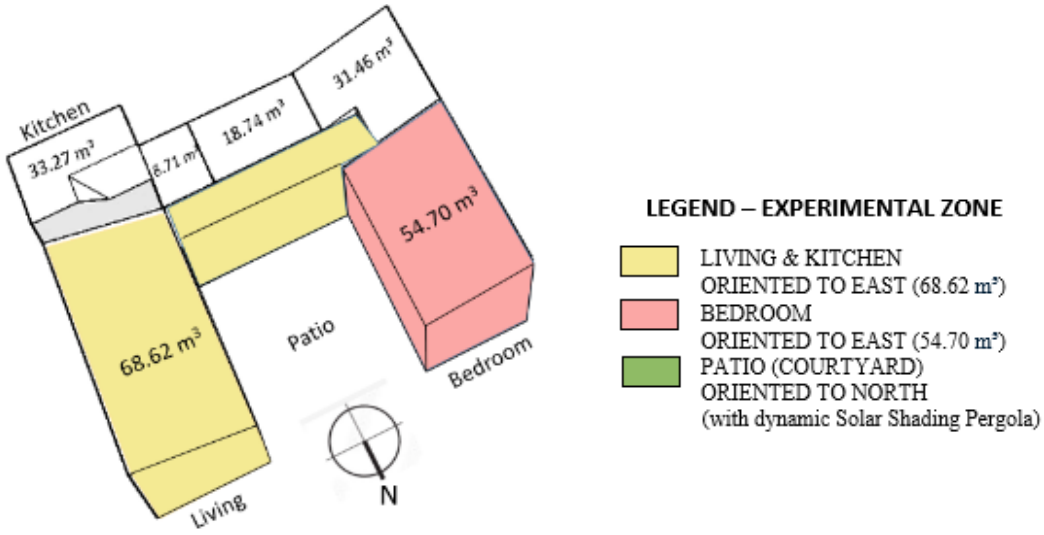


(a)



(b)

Figure 58: a) Location of BK Lab at TSC, Dubai, (Source: accessed on 5th Sept. 2025), b) Plan of BK Lab showing the experimental zone Living, Kitchen, Bedroom & Patio, (Source: Author)



(a) (b)

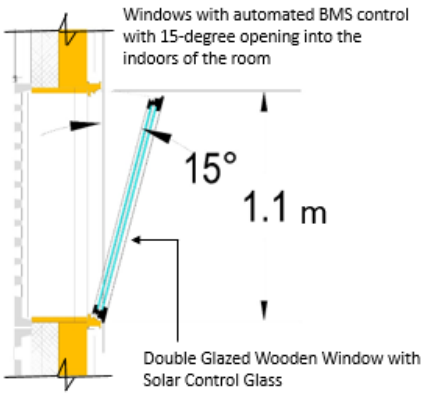
Figure 59: (a) The interior volume of the experimental zone, (b) The Legend for experimental zone, (Source: Author)



(a) (b)

Figure 60: (a) View of East-oriented Living room, (b) View of Living, dining/ Co-working space, (Source: Author)





(a) (b)

Figure 61: (a) View of West oriented Bed room facing north, (b) Plan of Window with opening angle, (Source: Author)

The west-oriented bedroom has two windows, W1 and W2 as in Fig. 61 (a), the east-oriented living room with two windows, W3 and W4 as in Fig. 60 (a), and the kitchen with one double-glazed window, W5 as shown in the layout Fig. 58 (b). All the windows are double-glazed, of the same size (1.1 × 2.2 m) and opening inwards at 15° to allow natural cross-ventilation as indicated in Fig. 61 (b). The living room and bedroom have a sliding, folding, double-glazed door each, measuring 3.8 m in length and 2 m in height, facing the patio with the plan as shown in Fig. 62 (c). The solar shading experiments test the potential of reducing solar heat indoors by using three layers of shading curtains, as indicated in the experiment scenario. The natural ventilation experiment scenario, involving window opening and closing, is performed by the automated BMS. Distech controls, a partner in the BaityKool project, offers technical, hardware, and software solutions for energy efficiency and occupant comfort, as indicated in section 3.4.

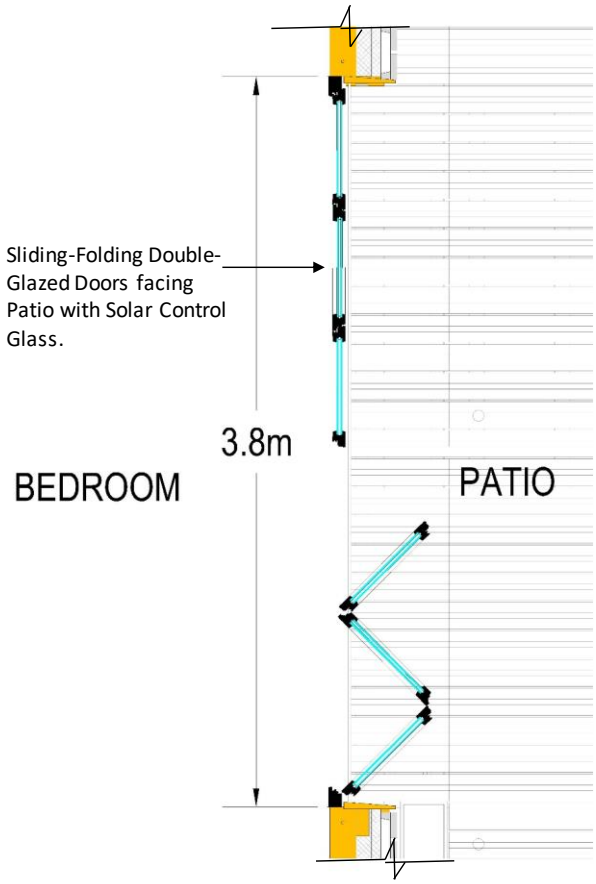
The patio (courtyard) measures 4.4 × 5.6 m and is centrally located between the living room and the bedroom, as shown in Fig. 62 (a). This area serves as the green core of the architectural layout, featuring a solar-paneled shading pergola at a height of 4.4 m to provide shade for the patio, as depicted in Fig. 62 (b). The East-facing living room and West-facing bedroom include glazed, sliding, folding doors that open onto the patio. These glazed doors are fitted with solar shading Roller Blind Blackout (RBB) curtains, fixed on the exterior side, as illustrated in Fig. 62 (a) to protect the indoor space from direct sunlight.



(a)



(b)



(c)

Figure 62: (a) View of Patio, North oriented claustra & solar shading pergola, (b) View of Patio with the shading solar pergola, (c) Plan of the Double-Glazed Sliding folding door from east oriented living and west oriented bedroom facing Patio, (Source: Author).

The living room and bedroom are connected by an internal corridor, as shown in Fig. 63 (a), with the north-facing wall accommodating the aquaponics system, which consists of a fish tank and a vegetative wall, as shown in Fig. 63 (b) and (c).



(a) (b) (c)

Figure 63: (a) View of Corridor with the Aquaponics wall oriented north, having the patio ventilator, (b) the vegetative wall of the aquaponics system, (c) View of aquaponics wall from the patio

The aquaponics wall on the patio, as shown in Figure 63 (c), faces North, while the indoor corridor is oriented toward the fish tank located to the North.

The vegetative wall has the zipgrow as shown in Fig. 64 (a) & (b), allowing natural cross ventilation when the patio's opaque opening, PV 1 & PV2, as indicated in Fig. 65, opens and closes. The open position of patio opaque opening PV 1 & PV 2 is as seen in Fig. 65 (a) and (c).

There are two opaque opening near the floor, measuring 1.1 × 0.76 m, as shown in Fig. 63 (b), allows natural cross ventilation from the patio to the indoors, opening at a 20° angle toward the exterior. The patio opaque opening operates on an automated BMS, permitting opening and closing based on a predetermined exterior temperature set by the occupant.

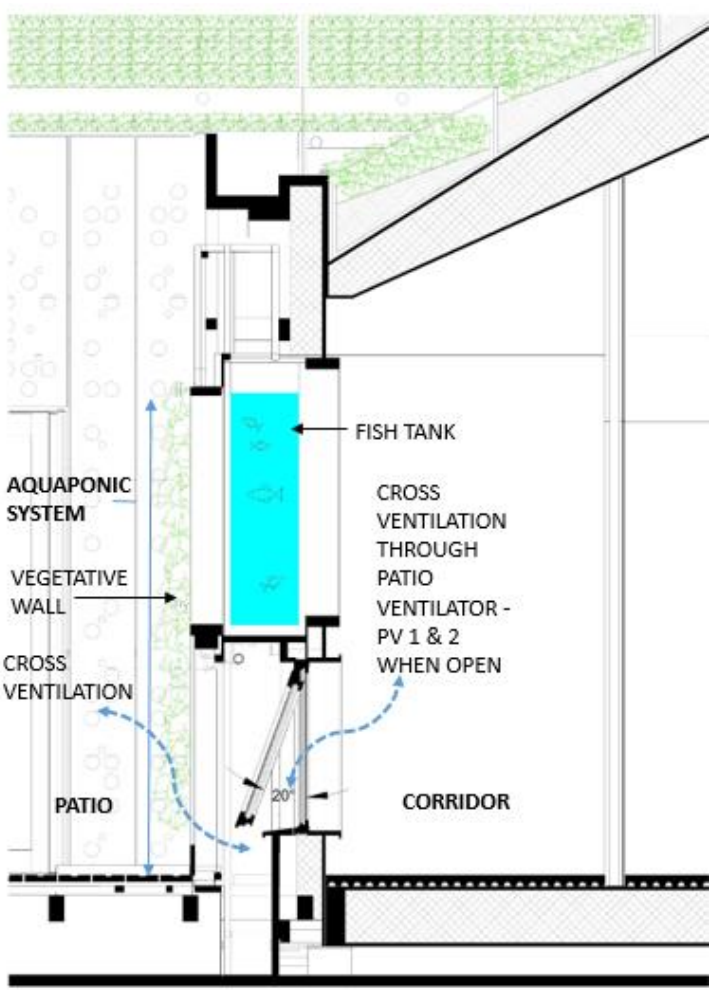


(a) (b)

Figure 64: (a) View of the aquaponics wall with the zipgrow allowing vegetation to grow, (b) Exterior view of the wooden battened panels of the aquaponics wall system allowing cross ventilation to the corridor through the patio opaque opening behind it, (Source: Author)

The experiments at the BaityKool living lab include scenarios with and without occupancy. The experiments involving occupancy feature a briefing process for participants, which includes the experiment's objectives, instructions, and protocols to follow, as well as obtaining consent for participation before the experiment. Records are maintained to document the number of participants involved in the experiments, their activities in the living lab during the experimental stay, clothing levels, and tasks performed in accordance with the experimental plan. Qualitative feedback is also collected based on their experiences.

The no-occupancy experiments enable testing a house in a more controlled environment, where conditions remain constant without the opening and closing of doors, human activities, or interference in the indoor space, which helps assess its impact on the indoor environment. Data collected during the experiments, using the instrumentation system, along with qualitative feedback on thermal comfort experiences, is recorded for analysis and the development of inferences and results.



(a)



(b)



(c)

Figure 65: (a) Sectional View of the Corridor with the Aquaponic wall oriented north, having the patio opaque opening in open position, allowing natural ventilation. (b) View of the Patio opaque opening PV 1 & 2 at the Corridor in closed position, (c) View of the Patio opaque opening PV 1 & 2 at the Corridor in open position allowing cross ventilation.

3.3 Experimental Design

The purpose of the experiments is to evaluate the potential for reduced solar heat gain and free natural cooling indoors under passive conditions. The objective is to test the prototype design based on the principles of bioclimatic architecture for extremely warm climates, aiming to achieve thermal comfort and energy balance through the use of passive strategies, including solar shading,

natural ventilation, and courtyard-based design. The lab-based experiments are crucial for assessing thermal comfort conditions indoors in the BaityKool prototype house, designed and built for extremely warm climates. Experiments on solar shading, natural ventilation, and patio shading, as indicated in Fig. 66, were conducted across various climatic seasons throughout the year to test the research question and evaluate potential benefits under different scenarios with architectural interventions.

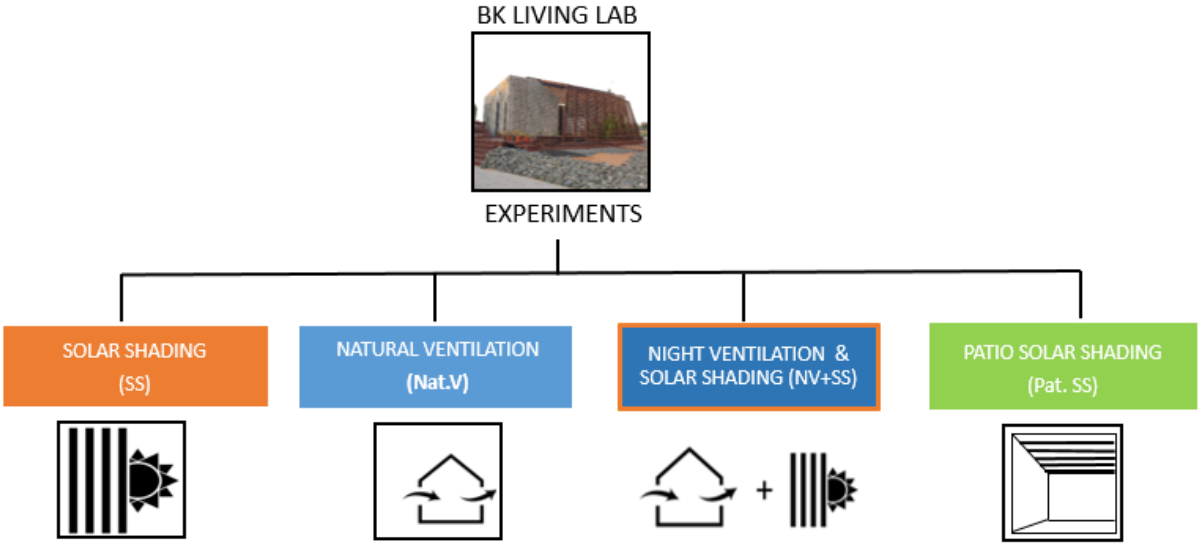


Figure 66: The graphical representation of the Experiments at BaityKool (BK) Prototype

Each experiment has experimental scenarios with varied architectural actions. For the solar shading, the scenarios test the application of different types of solar shading curtains fixed on the exterior and interior sides of the glazed window. For natural ventilation, the operation involves opening and closing the windows to allow natural cross-ventilation according to the experimental plan. For patio shading, it analyzes the shading benefits from architectural form and the use of the solar pergola based on the building orientation. The details of each experiment and its corresponding experimental scenario are outlined below.

3.3.1 Experimental scenario #1: Solar Shading (SS)

The objective of this experiment is to study and identify the potential benefits of solar shading through various types of shading curtains. The improvement potential in thermal comfort and visual comfort based on Standard EN 14501 [88] with the use of the BaityKool façades having the perforated UHPC envelope system specially designed and developed for extreme hot climates,

with the aim of reducing solar radiation indoors and providing sufficient visual comfort for occupants of the prototype and reduce indoor solar heat gain. Experiments were conducted in July, August, and September during the peak summer season in Dubai at the BaityKool Living Lab. The experiments evaluate the benefits of passive strategies in mitigating the impact of solar heat gain indoors and reducing energy demand for cooling without the use of air conditioning. All externally facing glazed windows feature fixed perforated UHPC panels with specially adapted perforations, detailing the rates and geometry of these perforations.as external skin shading to reduce direct sunlight, as shown in Fig. 68 (b). Double glazing with "Solar protection ultra N face 3" SGG Planitherm Ultra N, a high-performance, low-emissivity glass designed for excellent thermal insulation, with its solar control coating on the inner surface (Face 3) of a double-glazed unit, effectively controlling solar heat gain while allowing significant daylight and providing overall energy efficiency. Additionally, the glazed openings have vertical blinds controlled to be lowered when necessary, with the aim of reducing solar radiation indoors and providing sufficient visual comfort for occupants. The experimental zone has a window-to-wall ratio (WWR) of 22% for the living area oriented East and 24% for the bedroom-oriented West. The ESTIDAMA Pearl Rating System, a comprehensive framework rating the sustainable performance of buildings, prescribes a maximum WWR of 20% to 25% for most building types and orientations. Greater emphasis laid on glazing with lower Solar Heat Gain Coefficient (less than 0.25 ideal) and low U-Value to reduce conductive heat gain [89]. The Al Safat Green Building Regulation prescribes WWR to a maximum of 40% [17]. The difference in the indoor visual comfort with the use of the dynamic solar shading curtain and the UHPC perforated panels is evident from Fig. 68 (a), which shows the view of the living room with sunlight streaming in from the east during the morning 8 hours in July; Fig. 68 (b), depicts the shading achieved by the glazed window with the UHPC perforated panel external skin shading as in Fig. 67; and Fig. 68 (c), illustrates the dynamic solar shading curtain (ITC) effectively blocking sunlight from entering the indoors through the double-glazed window.



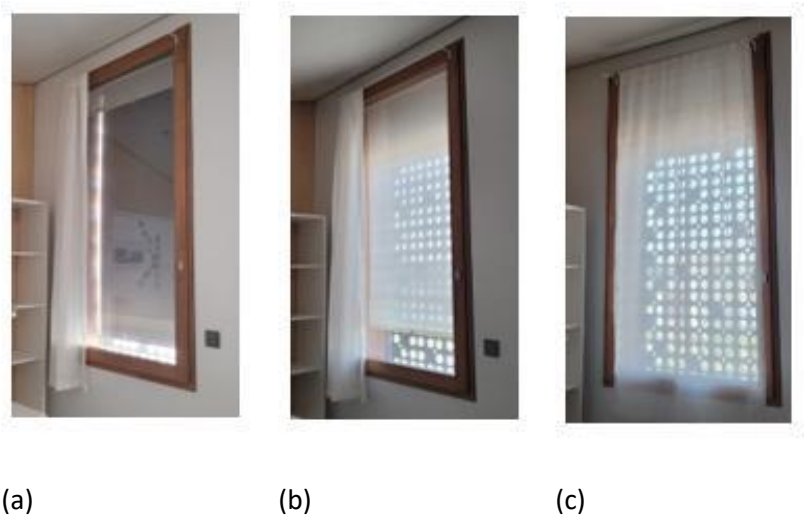
Figure 67: View of BK Lab with the UHPC panel external skin shading (Source: Author).



(a) (b) (c)

Figure 68: (a) View of Living room at BK lab with glazed windows and door having no curtain shade with sun rays falling at the indoors from the east at morning hours, (b) Interior view of glazed window with the UHPC panel external skin shading, (c) View of glazed window with ITC curtain closed for solar shading

The perforated fiber-reinforced concrete panel acts as the static ventilated skin for all external-facing windows. This panel serves as the primary layer of solar shading for the windows, enhanced by three additional layers of solar shading curtains that operate as a dynamic solar shading device, opening and closing as required to block sunlight from entering indoors. The first layer on the exterior is the Roller Blind Blackout (RBB), as shown in Fig. 69 (a). The second layer, also located on the exterior, is the External Translucent Roller Curtain (ETC), depicted in Fig. 69 (b), which functions as a dust barrier. The third layer is the Internal Translucent Cotton curtain (ITC), shown in Fig. 69 (c), fixed on the interior side of the window.



(a) (b) (c)

Figure 69: (a) Roller Blind Blackout (RBB), (b) Exterior Translucent Curtain (ETC) & (c) Interior Translucent Curtain (ITC).

The solar shading curtain material as designed for the external facing windows/ door:

(a) Roller Blind Blackout (RBB) - material composition: 100% polyester with an acrylic back coating, mass 280 - 450 g/m², thickness: 0.4 - 0.8 mm, creates a completely impermeable layer to light.

(b) Exterior Translucent Curtain (ETC) material composition: a blend of 60% polyester, 25%cotton, and 15% linen, mass 320-400 g/m², thickness 0.8-1.2 mm, shade coefficient 0.5-0.7, UV Radiation Blocking: ≥ 90%, Visible Light Transmittance (VLT): 25% - 45%.

(c) Interior Translucent Curtain (ITC) - Material Composition: Voile is a soft, lightweight woven 100% cotton fabric, with a mass of 50 - 80 g/m², softens harsh sunlight, creating a pleasant and ambient light quality.

The selection of solar shading experiments in July, August, and September was based on the summary of the climate study in Dubai, as in section 1.2.2, Table 2, indicating peak summer months with high temperatures ranging from 46.9 °C to 49.5°C in July, August, and September, with relative humidity of 69-78%. The climate season classification, as shown in Fig. 16, classifies climate season S6 as hot days and hot nights in Dubai. The comparison of climatic Seasons in Dubai annually, as in Fig.18, indicates S6 from May to October. The strategies of architectural action for very hot climates and peak summer seasons, with 'External Heat Protection' solar

protection for windows and doors at BaityKool, align with the Strategic directions and Classification of architectural actions (AA) for a very hot climate.

The experiment evaluates the performance of solar shading curtain devices installed on the exterior-facing windows and doors, alongside the perforated UHPC shading envelope system. The external-facing windows of the prototype featuring the perforated UHPC shading envelope system, without the use of shading curtains, are considered an experimental Reference (Exp. Ref.). The results for temperature and relative humidity in the indoor area of the experimental zone are compared with those under the experimental reference with windows to analyze the solar shading benefits offered by various types of shading curtains, following the experimental plan, as well as the solar shading advantages gained from the perforated UHPC.

The solar shading experimental scenarios with solar curtains, including RBB, ETC, and ITC, along with the abbreviations for occupancy status and scenario, are presented in Table 11. The graphical representation for solar shading experiment scenarios using solar curtains is shown in Fig. 70. The solar shading experiment settings during the summer season include the experiment zone occupancy status and indoor environment with or without air conditioning, as indicated in Table 12.

Table 11: Solar Shading experiments, experimental scenario with abbreviations

Experiment	**Experiment Abbreviation**	**Experiment Scenario**	**Scenario Abbreviation**
Experiment Reference	**Exp. Ref.**	No use of Solar shading Curtain, only the UHPC perforated envelope system shading the glazed window	**N. SSC**
Solar Shading Curtain:	**SSC**	Solar Shading: Roller Blind Blackout	**SS: RBB**
		Solar Shading: Exterior Translucent Curtain	**SS: ETC**
		Solar Shading: Interior Translucent Curtain	**SS: ITC**

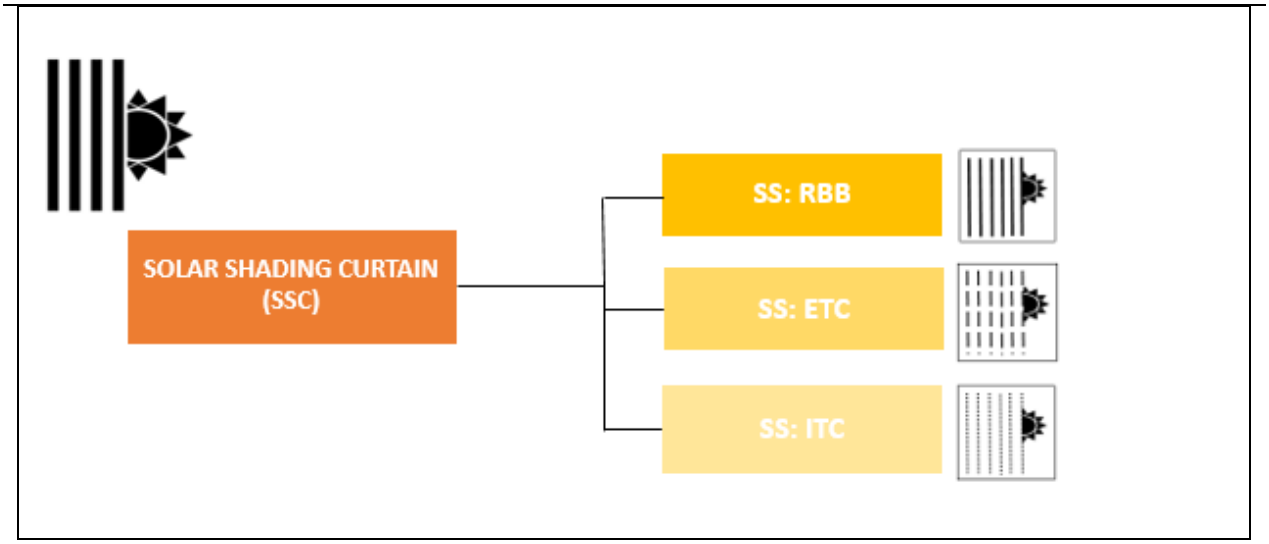


Figure 70: The graphical representation of the Solar Shading experiment scenarios

Experiment sets as in Table 12 was conducted over two consecutive days, with a baseline reference experiment (Exp. Ref) performed over two consecutive days without a solar shading curtain (SSC) either before or after each set of experiments. The results of the reference experiment were compared with those of the experiment that utilized the solar shading (SS) action with the shading devices RBB, ETC, and ITC. The Solar Shading experiments were performed in the peak summer months, July, August, and September. During occupancy, the experiments involved one to two residents in the living lab engaging in daily activities such as living, working, cooking, and relaxing. The residents carried out the experimental task of opening and closing the solar shading curtains according to the experimental plan and protocol during the occupancy period, while the researcher managed this task during the non-occupancy period.

Table 12: Solar shading experiment sets, indicating the period performed, the occupancy status of the living lab, and the condition of the indoor environment.

Experiment Sets for Solar Shading	**Experiment Month & Year**	**Duration for each experiment**	**Experiment Zone Occupancy Status during the experiment**	**Indoor Environment: Air conditioning / No Air conditioning**
1	**July** 2023	48 Hours	With Occupancy **(WOCC)**	No Air conditioning **(NAC)**
2	**Aug.** 2023	48 Hours	With No Occupancy **(NOCC)**	No Air conditioning **(NAC)**

3	**Sept.** 2023	48 Hours	With No Occupancy **(NOCC)**	No Air conditioning **(NAC)**

3.3.2 Experimental Scenario # 2: Natural Ventilation

The objective of the experiment is to study and identify the potential benefits of natural free cooling indoors in the BK living lab through passive means of natural ventilation. The windows of the experimental zone opened and closed during favorable weather conditions with a comfortable temperature range of 20-24 °C, as per ASHRAE standard 55 [67] at the outdoor site context of the BaityKool living lab. The experimental scenarios for the test zones, with a plan in place throughout the year, enable the assessment of bioclimatic strategies at the BaityKool living lab for achieving thermal comfort through day and night ventilation and night-time ventilation only. The two experiments involve architectural actions aimed at natural ventilation.

Table 13 lists the experiments and the scenarios with their corresponding abbreviations. The graphical representation for the natural ventilation experiment and scenarios is shown in Fig. 71. The experimental sets include a reference experiment (Exp. Ref.) as a neutral scenario, featuring no cross-ventilation setup conducted for two consecutive days prior to or following the Natural Ventilation scenarios. During the reference experiment, the external doors and windows of the house are kept closed, while the internal doors of the kitchen and bedroom remain open. The Natural Ventilation (Nat.V) experiment scenarios are conducted without occupancy to ensure a controlled indoor environment, preventing any impacts on indoor environmental conditions caused by the opening and closing of external doors for daily access and egress, as well as by occupant activities and metabolic heat.

Table 13: Natural Ventilation experiments, experimental scenario with abbreviations

Experiment	**Experiment Abbreviation**	**Experiment Scenario**	**Scenario Abbreviation**
Experiment Reference	**Exp. Ref.**	No natural ventilation was used, and all external doors and windows were closed throughout the experiment duration.	**N. Nat.V**
Natural Ventilation	**Nat.V**	Night Ventilation	**NV**
		Day and Night Ventilation	**DV+NV**

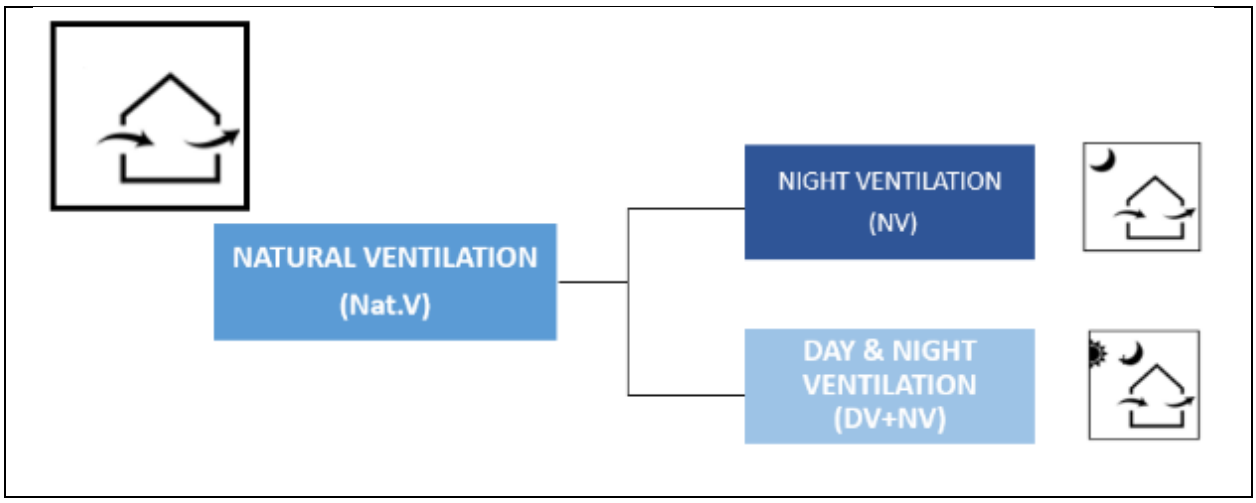


Figure 71: The graphical representation of the Natural Ventilation experiment scenarios

During the experiment for natural ventilation, the windows W3, W4 of the living area, W5 of the kitchen, and W1, W2 of the bedroom areas of the experimental zone open internally at 15°, along with the corridor patio ventilators PV 1 & PV2 opening externally to an angle of 20 °. The windows and ventilators are controlled for natural cross ventilation by an automated BMS, DISTECH controls. The potential cross ventilation pattern indoors as shown in Fig. 72.

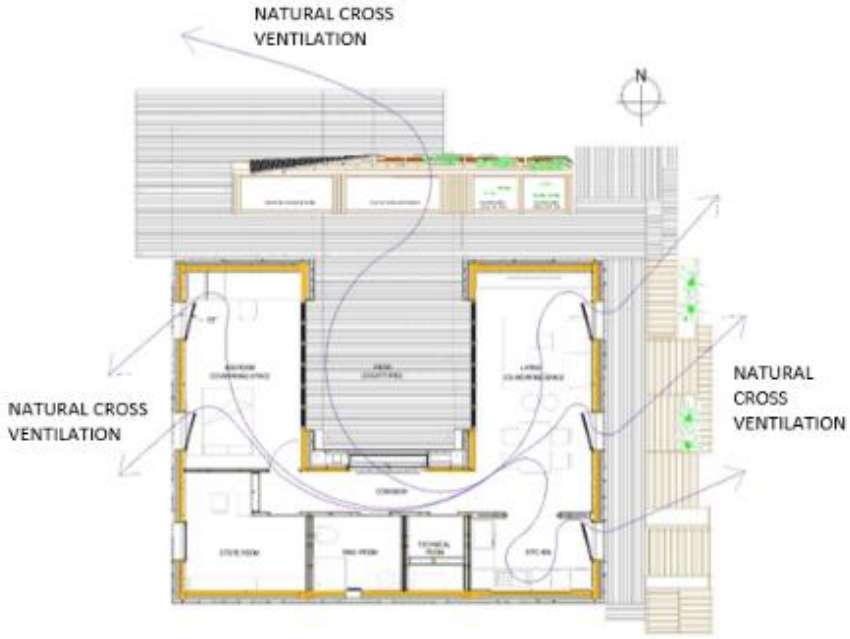
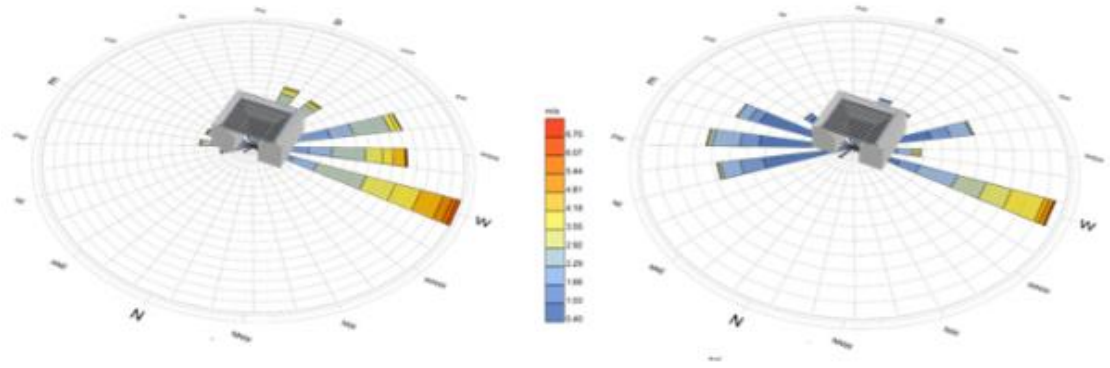


Figure 72: Natural Ventilation experiment strategy at BK living lab with windows of Bed room, Living & Patio ventilator open, doors of bedroom and kitchen open to capture wind and allow cross ventilation



Wind Speed (m/s)
City: Sustainable City, Country: UAE, Time Zone: 4.0,
Period: 1/1 to 12/31 between 6Hr. to 18 Hr. @ 1 hour interval
(a)

Wind Speed (m/s)
City: Sustainable City, Country: UAE, Time Zone: 4.0,
Period: 1/1 to 12/31 between 18 Hr. to 6 Hr. @ 1 hour interval
(b)

Figure 73: Wind rose at BK living lab from 1st Jan. to 31st Dec. 2023: (a) at 6.00 to 18.00 (b) 18.00 to 6.00

The yearly wind pattern at the BK living lab location, TSC, Dubai, is indicated in the wind rose. Fig. 73 (a) indicates the wind direction during 6.00 to 18.00 (day time) & Fig. 73 (b) indicates the wind direction from 18.00 to 6.00 (night time). The natural ventilation experiment settings during the winter and transitional seasons, including the experiment zone occupancy status and indoor environment with or without air conditioning, are indicated in Table 14.

Table 14: Natural ventilation experiment sets, indicating the period performed, the occupancy status of the living lab, and the condition of the indoor environment.

Experiment	**Experiment set**	**Duration for each experiment**	**Experiment Month & Year**	**Experiment Zone Occupancy Status during the experiment**	**Indoor Environment: Air conditioning / No Air conditioning**
Night Ventilation (NV)	1	48 Hours	January 2024	With No Occupancy **(NOCC)**	No Air conditioning **(NAC)**
	2	48 Hours	April 2024	With No Occupancy **(NOCC)**	No Air conditioning **(NAC)**
Day & Night Ventilation (DV + NV)	1	48 Hours	January 2024	With No Occupancy **(NOCC)**	No Air conditioning **(NAC)**

3.3.3 Experimental Scenario # 3: Night Ventilation and Solar Shading

The experiment in scenario 3 is a combination of scenarios 1 and 2. The objective of this experiment is to study and identify the potential benefits of free cooling indoors during the night through passive means and solar shading during the day. The windows of the experimental zone opened and closed during Table 15 lists the experiments with their corresponding abbreviations. The graphical representation favorable weather conditions with a comfortable temperature range of 20-24 °C, as per ASHRAE standard 55 [67] at the outdoor site context of the BaityKool living lab. for solar shading experiment scenarios using solar curtains is indicated in Fig. 74. The night ventilation with solar shading experiment settings during the transitional season, with the experiment zone occupancy status and indoor environment with or without air conditioning, are as indicated in Table 16.

Table 15: Night Ventilation with Solar Shading experiments, experimental scenario with abbreviations

Experiment	**Experiment Abbreviation**	**Experiment Scenario**	**Scenario Abbreviation**
Experiment Reference	**Exp. Ref.**	No natural ventilation was used, and all external doors and windows were closed throughout the experiment duration.	**N. Nat.V**
Night Ventilation with Solar Shading Curtain	**NV + SSC**	Night Ventilation & Solar Shading Curtain (RBB / ETC)	**NV+SS: (RBB / ETC)**

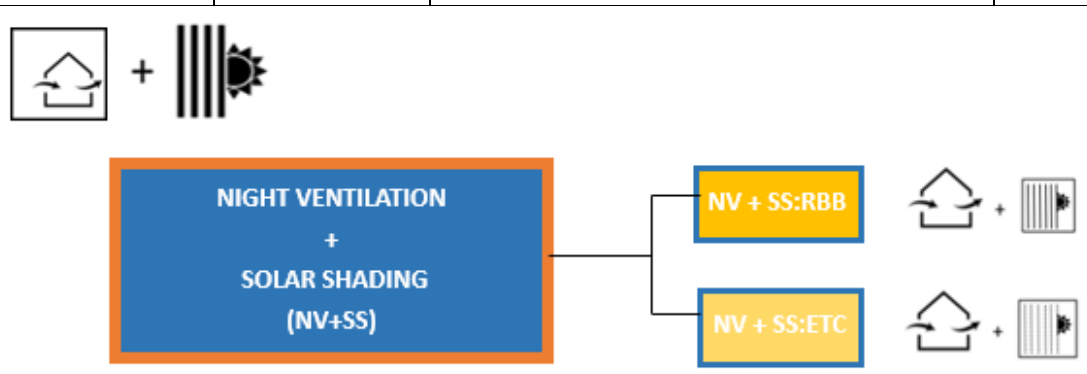


Figure 74:The graphical representation of the night Ventilation with Solar Shading experiment scenarios

The experiments conducted in April, the transitional season, assess the potential of reduced thermal mass temperature during the night, removing the stored heat absorbed during the day. The building

temperature resets to a much lower level than the baseline before the next day begins. During the day, the solar shading prevents direct solar heat gain and maintains a more stable indoor air temperature. The experiment integrates natural night ventilation with solar shading using shading curtains, Roller Blind Blackout (RBB), and External Translucent Curtain (ETC).

Table 16: Night ventilation with solar shading experiment sets, indicating the period performed, the occupancy status of the living lab, and the condition of the indoor environment.

Experiment	Experiment set	Duration for each experiment	Experiment Month & Year	Experiment Zone Occupancy Status during the experiment	Indoor Environment: Air conditioning / No Air conditioning
Night Ventilation & Solar Shading (NV+SS:RBB)	1	48 Hours	March 2024	With No Occupancy **(NOCC)**	No Air conditioning **(NAC)**
	2	48 Hours	April 2024	With No Occupancy **(NOCC)**	No Air conditioning **(NAC)**
Night Ventilation & Solar Shading (NV+SS:ITC)	1	48 Hours	March 2024	With No Occupancy **(NOCC)**	No Air conditioning **(NAC)**
	2	48 Hours	March – April 2024	With No Occupancy **(NOCC)**	No Air conditioning **(NAC)**

During the experiment for natural night ventilation and solar shading, the windows W3, W4 of the living area, W5 of the kitchen, oriented east, and W1, W2 of the bedroom areas, oriented west, open internally at 15°. Also, the corridor patio ventilators, PV 1 & PV2, open externally at an angle of 20°, oriented north, and are open at night only from 22:00 to 6:00. The solar shading curtains RBB / ETC are closed for all the external-facing glazed doors and windows during the day from 7.00 to 19.00 hours. An automated BMS, DISTECH, controls the windows, ventilators, and solar shading curtains.

3.3.4 Experimental Scenario # 4: Patio Solar Shading

The experiments on Patio Environment test the benefits of bioclimatic strategies, including the architectural form and effect of a Solar Shading Pergola. (Pat.SS) in the courtyard. The patio with

the vegetative roof and the aquaponics system creates a microclimate that influences the indoor temperature of the prototype. The experiment in Table 17 enables the analysis of the temperature difference between the outside air temperature and relative humidity at the BaityKool living lab, the shaded patio, and the indoor temperature and relative humidity across the varied seasons. Experiments were also conducted at the patio with and without the dynamic solar shading pergola to analyze the difference in air temperature and relative humidity.

The Fig.75 graphically represents the Patio Environment experiment scenarios. Table 18 presents the experiment sets with the experiment scenarios and scenario abbreviations.

Table 17: Presents the patio shading experiment sets with the scenario and abbreviations

Experiment	**Experiment Abbreviation**	**Experiment Scenario**	**Scenario Abbreviation**
Patio Solar Shading	**Pat. SS**	Outside T/ RH	**Ext. Cont.**
		Shading from Architectural Form	**SS: AF**
		Shading from Solar Pergola	**SS: SP**
		Without Solar Shading Pergola	**WOSS: SP**

The architectural design of the BaityKool prototype features its three-dimensional form and patio solar shading pergola, providing shade to the wooden floor and the external perforated, fiber-reinforced concrete paneled walls facing the patio. Fig. 76 illustrates the shaded patio viewed from various angles within the patio.

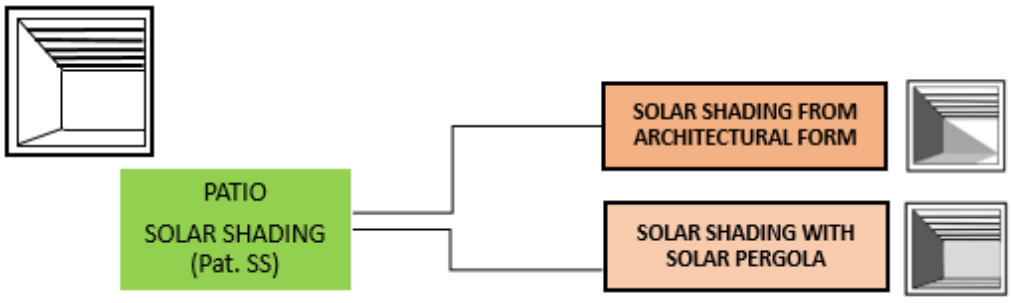


Figure 75: The graphical representation for the Patio Environment with the solar shading effect

Table 18: Presents the Patio Solar Shading experiment sets, indicating the period performed, the occupancy status of the living lab, and the condition of the indoor environment.

	Experiment set	**Duration for each experiment**	**Experiment Month & Year**	**Experiment Zone Occupancy Status during the experiment**	**Outdoor Environment: Conditioned / Naturally Ventilated**
Patio Solar Shading (Pat. SS)	1	48 Hours	January 2024	With No Occupancy **(NOCC)**	Naturally Ventilated
	1	48 Hours	Mar. 2024	With No Occupancy **(NOCC)**	Naturally Ventilated
	1	48 Hours	April 2024	With No Occupancy **(NOCC)**	Naturally Ventilated
	1	48 Hours	July 2023	With No Occupancy **(NOCC)**	Naturally Ventilated
	1	48 Hours	August 2023	With No Occupancy **(NOCC)**	Naturally Ventilated
	1	48 Hours	Sept. 2023	With No Occupancy **(NOCC)**	Naturally Ventilated
	1	48 Hours	May 2024	With No Occupancy **(NOCC)**	Naturally Ventilated – with and without Solar Shading Pergola

The shadows at patio in may demonstrated in Fig. 76 (a) at 10 am, Fig. 76 (b) at 11 am, and Fig. 76 (c) at 12 noon. The patio shade was achieved due to the orientation of a C-shaped pattern with the frontal opening facing north. The thermal comfort conditions in the courtyard were evaluated during the summer, winter, and transitional periods. The microclimate benefits of the patio were analyzed to understand the effects of patio shading under passive conditions.



(a) (b) (c)

Figure 76: Solar shading at Patio (a) the view of claustra at BK entry facing north & solar pergola, (b) Patio view with shading from architectural form and solar pergola, (c) the shading effect on the façade using the solar pergola

3.3.5 Summary of the Experimental Plan at BK living Lab

The experimental plan for the scenarios involving solar shading, natural ventilation, and patio environments was conducted throughout the year, focusing on peak summer, winter, and transitional periods, as indicated in Fig. 77.

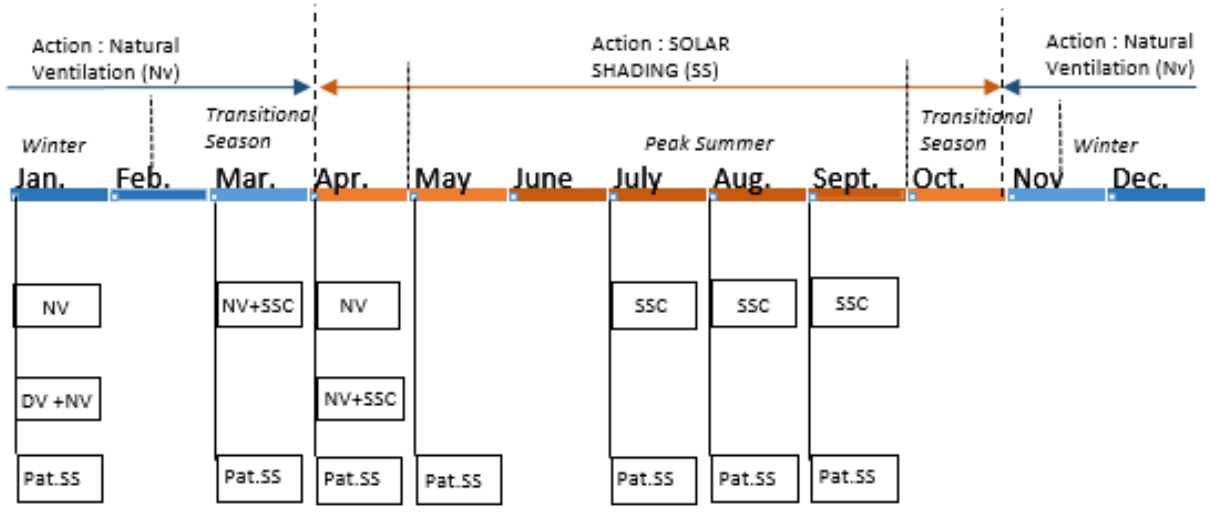


Figure 77: The experimental plan across the seasons at BK living lab in Dubai, UAE

3.4 Experimental Protocol

3.4.1 Experiment Solar Shading

The experiment enables to develop an energy conservation strategy by improving the indoor thermal comfort conditions through the use of solar shading devices for exterior-facing doors and windows of the BaityKool prototype. The performance of shading for external-facing openings based on orientation at different times of the day and varying climatic conditions examined. The impact on indoor thermal comfort conditions throughout the year, including peak summer, winter,

and transitional periods analyzed. The purpose of the experiment is to study the potential for improving indoor thermal comfort conditions through the shading of glazed doors and windows in the envelope system. The performance of shading devices is analyzed for their potential to reduce energy consumption in air conditioning, aiming to conserve energy through passive strategies.

Hypothesis:

- The shading device can effectively reduce the solar heat gain indoors through the glazed windows and doors.
- Lower temperatures can potentially reduce the operating hours of the air conditioning unit, thereby saving energy.

Experiment procedure:

Experiments conducted without air conditioning in the BaityKool living lab for the planned experimental scenarios:

- **With occupancy serving as a home** for only the experiment in July, with one occupant at the living lab.
- **With no occupancy**, to maintain a controlled, constant indoor environment of the lab.

Step-by-step instructions for running the experiments:

- Experimental scenarios will adhere to the experimental plan, with baseline reference data recorded for specific times and durations without solar shading curtains, followed by experiments involving solar shading curtains as indicated in scenario Figure 67, Table 3.1.
- The experimental setup was based on a baseline Reference (Ref.) scenario with no cross ventilation and no solar shading for the externally facing windows of the experimental zone Liv., Kit, BRm. The reference setup was conducted for three consecutive days (day and night) prior to the experimental day for each designed solar shading for the externally facing windows and doors.
- The experiment with the action of each solar shading device done for next three consecutive days and night. All external facing Windows and doors kept in closed position during the experiments. During each of the solar shading experiments the devised curtain closed at 7am and opened at 7 am on the third day of the experiment.
- All the instrumentations: sensors checked for their working condition and calibrated readings, along with battery power and memory status for the data loggers. The automated

building management system, weather station, and its data loggers were also ensured for their operational status, including the energy-efficient data backup status.

- All exterior-facing doors and windows of the prototype remained closed in all rooms for the duration of the experiment.
- The internal doors of the kitchen, bedroom, and washroom remained open during the duration of the experiment.
- The technical room door remained closed throughout the experiment.
- The occupancy status of the living lab is recorded according to the experimental plan. For experiments involving lab occupancy, details such as the number of occupants, their gender, age, and nationality are logged. Additionally, the occupancy date, time, duration of stay, indoor occupancy area, activity or function, and clothing during the stay are documented at regular intervals.
- In experiments involving occupancy, the objectives, plans, and protocols must be communicated to the participants. Additionally, consent for participation in the experiment and research process, as well as an agreement to adhere to the experimental protocol, should be obtained before the commencement of the experiment.
- In the case of experiments with no occupancy, the researcher should conduct the experiment setup according to the plan and protocol.
- The air conditioning system was switched off everywhere in BaityKool during the experiment, with only the exhaust system operating at the cooling unit. The set exhaust parameters were recorded from the DISTECH control Building Management System at the BK living lab.
- Sensors and data loggers in all experimental rooms were checked for proper functioning. The dish tech and weather station data loggers were inspected for data acquisition.
- The data from the temperature and relative humidity sensors was calibrated and cross-checked with a separate independent sensor unit before and during the experiment.
- All data have been acquired and lab records have been systematically compiled in the experiment format sheet.

3.4.2 Experiment Natural Ventilation

To test the impact of natural ventilation on the indoor thermal comfort of the prototype under passive conditions without the use of air conditioning. Examine the impact of natural cross ventilation on indoor temperature and relative humidity. The impact of the thermal mass of the envelope system on improving indoor temperature by capturing cool air during cross-ventilation hours was tested. The potential for energy savings through free cooling at night when exterior temperatures drop is explored

Hypothesis:

- The natural cross ventilation strategies have the potential to create thermal comfort during winter and transitional seasons while saving energy.
- Natural ventilation flushes out heat and effectively resets the building's thermal mass to a lower temperature before the beginning of the next day.

Experiment procedure

Experiments were conducted without air conditioning and occupancy in the BaityKool for the planned experimental scenarios.

Step-by-step instructions for running the experiments:

- Experimental scenarios should follow the experimental plan, using the baseline reference data recorded for the specific time and duration without natural ventilation, followed by the experiments with natural ventilation as outlined in the scenarios.
- All the instruments, including sensors, were checked for their working condition and calibrated readings, as well as battery power and memory status for the data loggers. The automated building management system and weather station, along with their data loggers, had their energy backup status ensured for proper functioning.
- The experimental setup included a baseline Reference (Ref.) established for three consecutive days either prior to or following the experimental scenario. The baseline Reference (Ref.) served as a neutral scenario with no cross ventilation or solar shading. During the reference experiment, the external doors and windows of the house were kept closed, while the internal doors of the kitchen and bedroom remained open.
- The experiment scenario involved natural ventilation through Day and Night ventilation (DV+NV) conducted over 2 days (48 hours). The first day and night lasted for 24 hours,

during which the windows of the living room, kitchen, bedroom, and patio ventilator were opened at 7am and closed at 7 am the following day. On the second day of the experiment, there was no cross ventilation during the day and night. The externally facing windows and doors remained uncovered by curtains or roller blinds for solar shading on both reference and experimental days, and the internal doors of the kitchen and bedroom were kept open for cross ventilation. During the Day Ventilation (DV) & Night Ventilation (NV) experiment, the patio door remained closed, with the doors only opened to set up the experiment at the beginning and end of the process.

- The experiment scenario with the action Night Ventilation (NV) was conducted over a 24-hour period. On the first day, the windows of the living room, kitchen, bedroom, and patio ventilator were opened at 10 pm and closed at 7 am the following day. On the second day, no cross ventilation was utilized. All external-facing windows and doors had no curtains or roller blinds for solar shading during both days of the experiment. Throughout the Night Ventilation (NV) experiment, the patio-facing door remained closed, with the doors opened only to set up the experiment at the beginning and end.
- For the night ventilation experiment scenarios, the Patio Ventilator is closed during the day and open at night only. The windows are closed during the day and open at night for cross ventilation.
- The internal doors of the bedroom and kitchen are kept open when the indoors are naturally ventilated. This allows for cross ventilation between the rooms indoors.
- The experiments were conducted using only passive cooling conditions, without any air conditioning, relying solely on the exhaust system operating at the cooling unit. The exhaust parameters were recorded from the DISTECH control Building Management System at the BK living lab.
- The Natural Ventilation (Nat.V.) experiment scenarios were conducted without occupancy to create a controlled indoor environment, eliminating any effects from changes in the indoor environment caused by activities, or the opening and closing of external doors for access and egress necessary for daily functions.

3.4.3 Experiment Natural Night Ventilation and Solar Shading

To test the impact of natural night ventilation and solar shading on the indoor thermal comfort of the prototype under passive conditions without the use of air conditioning. Examine the effects of

natural cross ventilation at night and perform solar protection during the day for the external-facing doors and windows. Assess the potential natural diurnal (day-night) temperature swing in an extreme warm climate and reduce solar heat gain.

Hypothesis:

- The natural night cross ventilation strategies have the potential to create thermal comfort during winter and transitional seasons and save energy for mechanical cooling.
- Combining natural ventilation with solar shading can prolong the period of indoor thermal comfort and enable free natural cooling.

Experiment procedure

Experiments were conducted without air conditioning and occupancy in BaityKool for the planned experimental scenarios.

Step-by-step instructions for running the experiments:

- Experimental scenarios should follow the experimental plan, using the baseline reference data recorded for the specific time and duration without natural ventilation, followed by the experiments with natural ventilation and solar shading as outlined in the scenarios.
- All the instruments, including sensors, were checked for their working condition and calibrated readings, as well as battery power and memory status for the data loggers. The automated building management system and weather station, along with their data loggers, had their energy backup status ensured for proper functioning.
- The experimental setup included a baseline Reference (Ref.) established for three consecutive days either prior to or following the experimental scenario. The baseline Reference (Ref.) served as a neutral scenario with no cross ventilation or solar shading. During the reference experiment, the external doors and windows of the house were kept closed, while the internal doors of the kitchen and bedroom remained open.
- The experimental scenario involving Night Ventilation and Solar Shading (NV + SS: RBB, ETC) consists of a night ventilation experiment lasting 24 hours on the first day, followed by a second day without night ventilation, during which solar shading is applied for the next two days (48 hours). All external-facing windows and doors were kept closed with solar shading. The patio-facing door remained closed, with the doors opened only to set up the experiment at the beginning and end.

- During each of the night ventilation and solar shading experiments, the devised curtain closed at 7am and opened at 7 am on the third day of the experiment.
- For the night ventilation experiment scenarios, the Patio Ventilator is closed during the day and open at night only. The windows are closed during the day and open at night for cross ventilation.
- For the night ventilation with solar shading experiments, the shading devices included a roller blind, an external translucent curtain, and an internal translucent curtain, which were closed during the second and third days of the experiment.
- The internal doors of the bedroom and kitchen are kept open when the indoors are naturally ventilated. This allows for cross ventilation between the rooms indoors.
- The experiments were conducted using only passive cooling conditions, without any air conditioning, relying solely on the exhaust system operating at the cooling unit. The exhaust parameters were recorded from the DISTECH control Building Management System at the BK living lab.
- The Natural Ventilation (Nat.V) experiment scenarios were conducted without occupancy to create a controlled indoor environment, eliminating any effects from changes in the indoor environment caused by activities, or the opening and closing of external doors for access and egress necessary for daily functions.

3.4.4 Experiment Patio shading

The experiments investigate the advantages of courtyard-based design with bioclimatic strategies for extreme warm climates. Analyze how architectural form impacts shading in the courtyard. Enables the comparison of the temperature and relative humidity between the exterior site context and the courtyard. This helps to evaluate how bioclimatic strategies can enhance the thermal comfort conditions in the courtyard.

Hypothesis:

- The architectural form and bioclimatic strategies have the potential to create thermal comfort in the courtyard (Patio) during certain periods in warm climates.
- The thermal comfort condition in the courtyard with passive natural cooling is sometimes more refreshing than indoors and creates a healthy living environment.

Experiment procedure

Experiments were conducted in the patio under passive conditions, without any active cooling devices like fans or water coolers.

Step-by-step instructions for running the experiments:

- The sensors for air temperature, operative temperature, and relative humidity are installed at the patio in the central position, at a height of 1.2 meters from the finished floor level.
- All instrumentations, including sensors, were checked for operational condition and calibrated readings, as well as battery power and memory status for the data loggers. The automated building management system, weather station, and its data loggers were also verified for proper functioning, alongside the energy wiser data backup status.
- The solar shading pergola on the patio remained in a closed position throughout the duration of the experiment, both day and night.
- Patio experiment with occupancy was only conducted in July, the peak summer season.
- No occupancy on the patio during the peak summer season in August and September, the winter season in January, and the transitional season in March and April. Experiments with no occupancy enable a controlled environment without variations in temperature and relative humidity caused by activities, including the opening and closing of external doors for access and egress by occupants for daily functions.
- The external doors of the prototype remained closed during the experiments with no occupancy, allowing only human intervention at the beginning and end of the experiment.
- The aquaponics system operated during the experiments.
- The patio vegetation receives irrigation daily at 7 am. The roof vegetation is irrigated at 7 pm and 7 p.m. for 10 minutes, controlled by an automated irrigation system via the remote smart device application and the building management system.

3.5 Instrumentation, tools & measure parameters

The parameters for measuring thermal comfort are Air Temperature (T) °C, and Relative Humidity (RH) % collected for each room in the experimental zone. Weather data is acquired from the localized weather station installed at the BK living lab. The location of the sensors and data loggers in the experimental zones is indicated in Fig. 78.

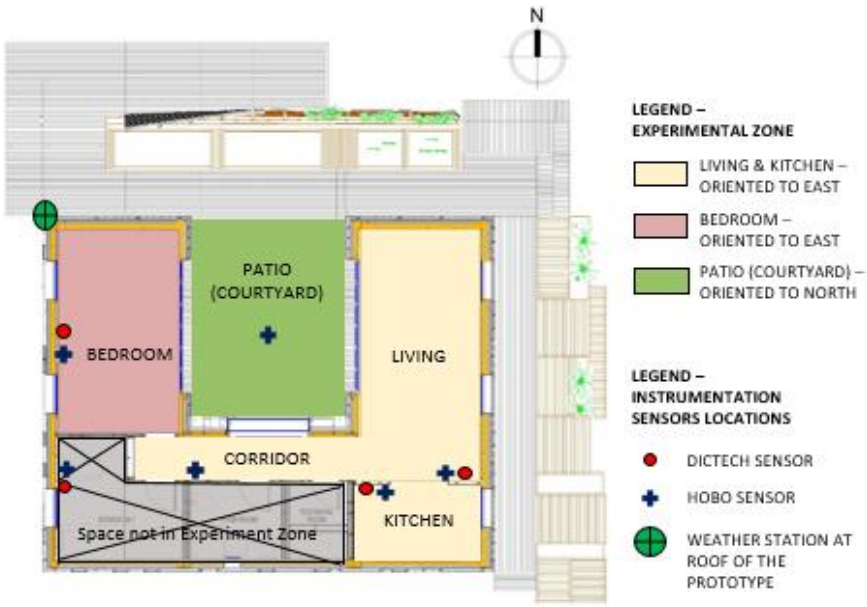


Figure 78: BK living lab layout with the instrumentation sensor locations marked in the experimental zone

- The DISTECH Allure™ EC-Smart-Air Series Black Globe Sensor, illustrated in Fig. 79 (a) and (b), is installed in the indoor living lab on the walls of the Living Room, Kitchen, and Bedroom, measuring Operative Temperature (T) in °C, Relative Humidity (RH) in %, and CO2 levels. These measurements are displayed on fixed HORYZON-C IP-based capacitive multi-touch color display monitors in the Living Room and on Allure UNITOUCH™ devices in each room, as shown in Fig. 79 (b). The EC-gfx Program automates the capture, logging, and display of these measurements from ECLYPSE controllers or EC-Net systems on laptops and smart devices, as depicted in Figure 79 (c).



(a) (b) (c)

Figure 79: (a) DISTECH Allure™ EC-Smart-Air Series Black Globe Sensor for Temperature, RH & CO_2 (b) DISTECH display in rooms for viewing real-time Temperature, RH & CO_2, (c) DISTECH control Program at the Lab computer

Temperature Sensor

Type 10 kΩ NTC

Thermistor Range 5°C to 40°C

Accuracy Sensing component; ±0.20°C , Overall accuracy; ±0.50°C

Resolution 0.1°C

Humidity Sensor

Accuracy ±3%

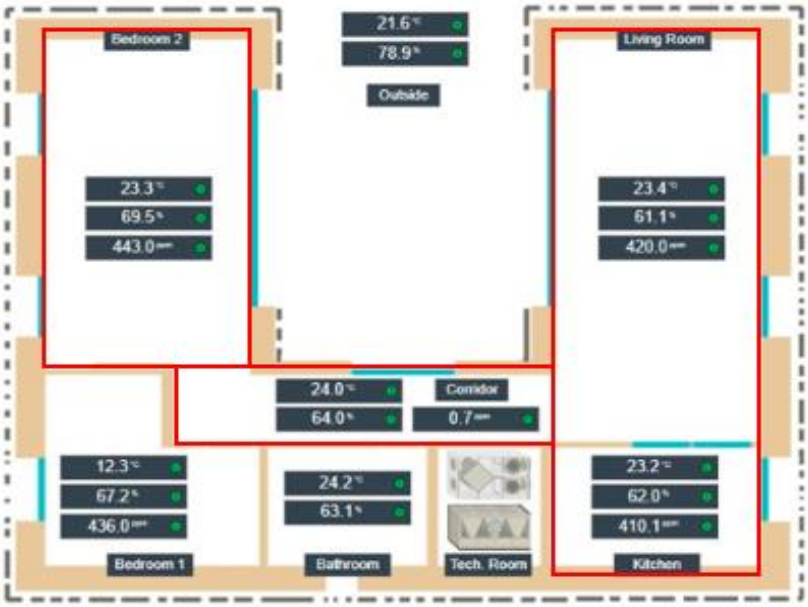
Resolution 1%

CO_2 Sensor

Measurement Range 0 to 2000 ppm

Operating Elevation 0 to 16000 ft (0 to 4877 m)

CO2 Accuracy1 400-1250 ppm ± 30 ppm or 3% of reading, whichever is greater 1250-2000 ppm ±5% of reading + 30 ppm



(a)



(b)



(c)

Figure 80: (a) REALTIME DATA for the Temperature, RH & CO_2 seen on the house plan at the DISTECH control Program on any smart device (b) DISTECH sensor location in the experiment zone living. (c) DISTECH sensor location in the experiment zone, Bedroom

- Onset HOBO UX100 Data Logger measures and transmits temperature and relative humidity to smart devices and Windows computers. The sensor locations, as shown in Fig. 80 (a) (b) & (c), are installed indoors in the living lab on the walls of the living room, kitchen, and bedroom at a height of 1.2 m. The sensors are shown in Fig. 81.



Figure 81: Onset HOBO UX100 Data Logger sensor installed at location in experiment zone, living & Bedroom for Temperature & RH

Sensor at the Patio (Courtyard)

Portable Globe Temperature Sensor with Onset HOBO UX100-014M Thermocouple Data logger as in Fig. 82 (c), collecting measures using a black globe temperature sensor fixed on a portable tripod fixed at 1.2 m from finished floor level as in Figure 82 (a), (b).



(a) (b) (c) (d)

Figure 82: (a)Globe Temperature Sensor with Hobo ONSET data logger, (b) View of the portable tripod Globe Temperature Sensor with Data logger, (c) Onset HOBO UX100 Data Logger sensor, (d) weather shield with Onset HOBO UX100 Data Logger sensor for capturing data for air temperature at Patio

Ambient Weather Solar Radiation Shield for housing the Onset HOBO UX100 Data Logger for temperature & relative humidity as in Fig. 82 (d)

Temperature Sensor

Range -20°C to 70°C

Accuracy ±0.21°C from 0°C to 50°C,

Resolution 0.024°C at 25°C

RH Sensor

Range 1% to 90% (non-condensing)

Accuracy ±2% from 20% to 80% typical to a maximum of ±4.5% including hysteresis at 25°C; below 20% and above 80% ±6% typical

Resolution 0.01%

- Weather Station: The data is obtained from the context of the BaityKool living lab at The Sustainable City, Dubai, using the DAVIS Wireless Vantage Pro2 Weather Station. The weather station is installed on the roof of the prototype, as shown in Figure 80, with the standard radiation shield and Weather Link Console mounted indoors to navigate, view, and analyze data. The data is logged in the Weather Link Cloud and can be accessed remotely. The sensor suite includes outdoor temperature and humidity sensors housed in a passive radiation shield, dew point, wind speed, wind direction, rainfall, wind chill, heat index, barometric pressure, and solar radiation. It provides data with scientific precision and near real-time updates.

Temperature Sensor Measuring Range: -40°C to 65°C

Temperature Accuracy: ±0.3°C

Method: A Silicon PN junction diode within a radiation shield to protect against solar radiation and heat sources.

Relative Humidity Sensor Measuring Range: 1 to 100% RH

Outside Humidity Accuracy: ±2% RH, Method: Film capacitor with a drift of less than 0.25% per year.

Wind Speed Measuring Range: 3 to 290 km/h (2 to 200 mph)

Wind Speed Accuracy: ±3 km/h (±2 mph), Method: Wind buckets and a Hall effect sensor.

Wind Direction Measuring Range: 0 to 360°

Wind Direction Accuracy: ±3°, Method: Wind vane with potentiometer.

Rainfall Accuracy: ±3% of total or +0.25 mm at most for intensities up to 100 mm/h

Method: A patented Aero Cone Rain Collector with a self-emptying, tipping trough system.

Barometric Pressure Accuracy: ±1.0 hPa, Measuring Range: 540 to 1100 hPa



(a) (b) (c)

Figure 83: (i) View of DAVIS Wireless Vantage Pro2 Weather Station at BK lab site on roof, (ii) View of the DAVIS Wireless Vantage Pro2 Weather Station, (iii) Weather station display at the Technical room of the BK lab

The data is collected every 15 minutes over a 24-hour period, and the Davis weather station's data logger stores the captured data in cloud storage with remote access. Data is compiled daily in the format of the experiments. The data is analyzed for specific dates and times, with a study conducted to compare different parameters and develop analysis, observations, and conclusions.

3.6 Data analysis procedure

The experiments have been proposed to test the impact indicators for the actions of the Bioclimatic design to characterize the effects on the indoor air temperature of the BaityKool prototype. The experiments proposed for the actions of the dynamic solar shading curtains to understand the potential reduction in air temperature with the reduced solar heat gain indoors, leading to lowered energy demand for cooling load, and improve thermal comfort indoors with passive strategies. The experiment proposed for natural ventilation test the advantages of diurnal (day-night) temperature swing in the extreme warm climate of Dubai, the potential of free cooling of indoor with night ventilation and, the effective resetting of the building's thermal mass to a lower temperature before the next day begins, this reduce the peak load the next day. The experiment combining the night ventilation with solar shading test the passive cooling strategy free cooling and flushing out heat at night and the solar shading trapping the coolness inside. Test the heat sink aspect of the pre cooled thermal mass of the interior absorbing the heat gain during the day. The performance of the envelope system tested for its ability being a thermal barrier minimizing heat gain in the extreme warm climate and maintain the temperature stability with its thermal mass and insulated structure. The experiment at the Patio tests the benefit of solar shading achieved by the architectural form

and its orientation. The difference in temperature and microclimate at the patio with and without a solar shading pergola designed for the extreme warm climate.

The experiments objectively measure the physical phenomena for the thermal comfort parameters, air temperature, and relative humidity, establishing the significant relationship between the Bioclimatic interventions for the extreme warm climate and the outcomes. The experimental data for the thermal comfort parameters, air temperature, and relative humidity are analyzed for the indoor space of the BaityKool living lab and at the patio during the experiments with no actions and with actions based on impact indicators. The experiment was performed with no occupancy and no air conditioning except for the Solar Shading experiment in July with one occupancy and no air conditioning as indicated in Table 12, Fig.70. The experiment scenario for Natural Ventilation as indicated in Table 14, Fig. 71. The Night Ventilation and Solar Shading experiments as indicated in Table 16, Fig. 74. The Patio shading experiments as indicated in Table 18, Fig.75. The experiments plan as in Fig.77 across the seasons at BK living lab in Dubai, UAE enable to analyze the performance of the prototype capturing full seasonal variability. The experiment's data analysis compares the effects of actions on bioclimatic systems with no action considered as a reference. The results of experiments conducted across the season for the scenarios are compared to facilitate a discussion and conclusion. This comparison aims to assess whether the performance predicted in the simulation at the design stage aligns with the performance results obtained during the SDME 2018 competition phase. Determine the potential of Bioclimatic design of the BaityKool for the extreme warm climate, the validation on the performance of the actions using only passive strategies in minimizing active energy use annually.

3.6.1. Equation for Experiment Analysis: Solar Shading & Natural Ventilation

- **Indoor Air Temperature reduction with Action:**

The equation represents temperature reduction achieved by the Action, Solar Shading / Natural Ventilation, during the experiment scenarios within the specified time intervals for data collection, is calculated by Eq.(2).

$$\Delta T^{Room}_{air,EXP}(t) = T^{Room}_{air,(SSC\,/\,Nv).}(t) - T^{Ext}_{air,Exp}(t) \qquad \textit{Eq. (2)}$$

where

$T^{Room}_{air,(SSC\ /\ Nv)}$ is the temperature of the room in the experimental zone with action solar shading curtain or night ventilation (°C).

$T^{Ext}_{air,.Exp.}$ is the exterior context of the lab during the experiment action (°C).

(t) is the Time interval between the two measures during the experiment (s).

$\Delta T^{Room}_{air,EXP}$ is the temperature difference achieved with the experiment (°C).

- **Indoor Air Temperature Reduction with No Action used as reference:**

The equation Eq. (3) represents the temperature reduction achieved from only the envelope system designed for very warm climates (without any impact of a shading curtain or natural ventilation), with data collection carried out at the same set time intervals then used in Eq. (2). This temperature reduction is hereafter used as a reference (REF) to estimate the impact of active bioclimatic action on temperature reductions.

$$\Delta T^{Room}_{air,REF}(t) = T^{Room}_{air,\ REF.}(t) - T^{Ext}_{air,\ Ref.}(t) \qquad \textit{Eq. (3)}$$

where

$T^{Room}_{air,\ REF.}$ is the Air Temperature in the room with no action as baseline experiment reference (°C).

$T^{Ext}_{air,\ Ref}$ is the Air Temperature at the exterior context of the lab on the same day of the reference experiment (°C).

(t) is the Time interval for the data collected from the room during the experiment(s).

$\Delta T^{Room}_{air,REF}$ is the Air Temperature difference with No Action at Experiment as baseline reference (°C).

- **Indoor air Temperature (°C) Action benefits:**

The equation Eq.(4) for temperature reduction benefits at BaityKool for the action involving scenarios in the respective rooms of the experimental zone is calculated by determining the temperature decrease achieved by the active bioclimatic action over the specified time interval.

$$\Delta T^{Room}_{air,\ ACTION\ Benefits}(t) = \left(\Delta T^{Room}_{air,EXP}(t) - \Delta T^{Room}_{air,REF}(t)\right) \qquad \textit{Eq.(4)}$$

where

$\Delta T^{Room}_{air,EXP}$ is the Air Temperature difference with Action at Experiment (°C).

$\Delta T_{air,\,REF}^{Room}$ is the Air Temperature difference with No Action at Experiment used as reference (°C).

(t) is the Time interval for the data collected from the room during the experiment(s).

$\Delta T_{air,\,ACTION\ Benefits}^{Room}$ is the Air Temperature reduction potential with active bioclimatic action (°C).

- **Indoor Air Temperature (°C) fluctuation at set interval with Action:**

The Reference 6 hours' temperature difference (REF) is first defined (Baseline temperature without the Action of Solar Shading Curtain or Natural Ventilation) calculated by Eq.(5)

$$(\Delta T_{air,\,REF}^{Room}) = T_{air,\,Ref.}^{Room}(t + 6\ hours) - T_{air,\,Ref.}^{Room}(t) \qquad \textit{Eq.(5)}$$

where

$T_{air\ Ref.}^{Room}$ (t) is the Air temperature (°C) in the room at time (t)

$T_{air,\,Ref.}^{Room}(t + 6\ hours)$ is the Air temperature (°C) in room 6 hours later.

$\Delta T_{air,\,REF}^{Room}$ is the reference air temperature (°C) difference over a 6-hour interval.

Then the corresponding entities, this time with the action of Solar Shading Curtain or Natural Ventilation, namely ($\Delta T_{air,EXP}^{Room}$) is then defined as follows. This is the difference between the consecutive T (°C) reading at every 6 hours interval calculated by Eq.(6).

$$(\Delta T_{air,EXP}^{Room}) = T_{air,\,EXP}^{Room}(t + 6\ hours) - T_{air,\,EXP}^{Room}(t) \qquad \textit{Eq.(6)}$$

Where

$T_{air,\,EXP}^{Room}$ (t) is the Air temperature (°C) during the experiment in the room at time (t)

$T_{air,}^{Room}$ (t + 6 hours) is the Air temperature (°C) during the experiment, 6 hours later.

$\Delta T_{air,\,EXP}^{Room}$ is the Air temperature (°C) difference during the experiment over a 6 hours' interval achieved with active bioclimatic action

- **Indoor Relative Humidity RH (%) fluctuation at set interval with Action:**

The Reference 6 hours' relative humidity (RH %) difference (REF) is first defined (Baseline relative humidity without the Action of Solar Shading Curtain or Natural Ventilation) calculated by Eq.(7).

$$(\Delta RH_{ar,\,REF}^{Room}) = RH_{air,Ref.}^{Room}(t + 6\ hours) - RH_{air,\,Ref.}^{Room}(t) \qquad \textit{Eq.(7)}$$

Where

$RH_{air,\,REF}^{Room}$ (t) is the Relative Humidity (%) in room at time (t)

$\mathbf{RH}_{air,\,Ref.}^{Room}(t + 6\ \text{hours})$ is the Relative Humidity (%) in room 6 hours later.

$\mathbf{\Delta\ RH}_{air,\,\mathrm{REF}}^{Room}$ is the reference Relative Humidity (%) difference over a 6-hour interval.

Then the corresponding entities, this time with the action of Solar Shading Curtain or Natural Ventilation, namely $(\mathbf{\Delta\ RH}_{air,\,\mathrm{EXP}}^{Room})$ is then defined as follows. This is the difference between the consecutive RH % reading at every 6-hour interval calculated by Eq.(8) .

$$(\mathbf{\Delta\ RH}_{air,\mathrm{EXP}}^{Room}) = \mathbf{RH}_{air,\,\mathrm{EXP}}^{Room}(t + 6) - \mathbf{RH}_{air,\,\mathrm{EXP}}^{Room}(t) \qquad \textit{Eq.(8)}$$

Where

$\mathbf{RH}_{air,\,\mathrm{EXP}}^{Room}$ (t) is the Relative Humidity (%) during the experiment in the room at time (t).

$\mathbf{RH}_{air,}^{Room}$ $(t + 6\ \text{hours})$ is the Relative Humidity (%)during the experiment in room 6 hours later.

$\mathbf{\Delta\ RH}_{air,\,\mathrm{EXP}}^{Room}$ is the Relative Humidity difference during experiment over a 6-hour interval in (%).

Solar Shading Curtains

The air temperature reduction achieved with the solar shading scenarios (EXP. SS: RBB, ETC, ITC) during the summer months of July, August, and September is compiled in the format of a Data table shown in Table 19. This table indicates the east-facing living room and west-facing bedroom of the experimental zone, for the experiment scenarios, as shown in Fig. 70, Table 12. The equations, Eq. (2), (3), and (4) are used to calculate the indoor air temperature reduction achieved based on the actions taken. The positive values of Air Temperature (°C) indicate the reduction achieved with action solar shading curtains expressed in terms of the month's minimum (Min.), maximum (Max.), and average (Avg.) values in 6-hour differences for the 48-hour experiment.

Table 19: Format of Data table for Air Temperature (°C) reduction achieved in 6 hours with Solar Shading Curtain: RBB, ETC & ITC with values of minimum, maximum & average in the east & west oriented rooms of the BaityKool living lab during the 48-hours experiment.

Solar Shading (SS)	**RBB**		**ETC**		**ITC**	
Air Temperature (°C) reduction at 6-hour difference	EAST	WEST	EAST	WEST	EAST	WEST
Minimum (Min.)						

Maximum (Max.)						
Average (Avg.)						

Natural Ventilation (Nat.V)

The Natural Ventilation (Nat.V) experiment conducted during winter and transitional seasons analyzed thermal comfort parameters, including air temperature (T°C) using Eq. (2) and Eq.(3 4), and relative humidity (RH%) using equations Eq. (7) and (8). This analysis compared the baseline reference of 'No Action' for Natural Ventilation with different natural ventilation scenarios. The potential for natural free cooling and its effect on thermal comfort parameters are presented in the results format shown in Table 20, which covers the east-oriented living room and west-oriented bedroom of the experimental zone. The positive values of Air Temperature (°C) indicate the reduction achieved with the action natural ventilation experiment scenarios expressed in terms of the month's minimum (Min.), maximum (Max.), and average (Avg.) values in 6-hour differences for the 48-hour experiment.

Table 20: Format of Data table for air temperature (°C) difference achieved at 6-hour difference with Natural Ventilation with values of minimum, maximum & average in the east & west-oriented rooms of the BaityKool living lab during the 48-hours experiment

	**Exp. NV + SS :RBB MAR 24**		**Exp. NV + SS : ETC APR 24**		**Exp. DV + NV JAN 24**		**Exp. NV Set 1 Jan 24**		**Exp. NV Set 2 April 24**	
	East	West	East	West	East	West	East	West	East	West
Natural Ventilation (Nv)	**Liv.**	**BRm.**	**Liv.**	**BRm.**	**Liv.**	**BRm.**	Liv.	BRm	Liv.	BRm.
Min										
Max										
Average										

3.6.2 Equation for Experiment Analysis: Patio Shading

The benefits of thermal comfort parameters, air temperature (°C) and relative humidity (%), were analyzed for winter, summer, and transitional months. The data were examined for the experiment scenario, as in Eq. (9), to identify differences between the patio microclimate and the external lab site measures.

The shading benefit of the patio for reducing air temperature (°C) at the patio, compared to the external ambient air temperature (°C), at the BaityKool prototype location for the experimental scenarios as shown in (cf. Fig. 75, Table 18).

$$\Delta T^{Patio}_{air,\ SHD..BENEFITS} = \left(T^{Patio,}_{air,}(t) - T^{EXT}_{air,}(t) \right) \qquad \textit{Eq. (9)}$$

where

$T^{Patio}_{air,}(t)$ is the Air Temperature (°C) at Patio in time (t)

$T^{EXT}_{air,}(t)$ is the exterior Air Temperature (°C) at the context location of BK living lab in time (t)

$\Delta T^{Patio}_{air,\ SHD..BENEFITS}$ is the Air Temperature (°C) difference at Patio achieved with solar shading pergola and architectural form.

The patio shading benefits for the Relative Humidity effect at the Patio when compared with external context relative humidity RH (%) at the BaityKool prototype location for the experimental scenario, as indicated in (cf, Figure 75, Table 18)

$$\Delta RH^{Patio}_{air,\ SHD\ BENEFITS} = \left(RH^{Patio,}_{air,}(t) - RH^{EXT}_{air,}(t) \right) \qquad \textit{Eq.(10)}$$

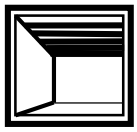
where

$RH^{Patio}_{air,}(t)$ is the Relative Humidity (%) at Patio in time (t)

$RH^{EXT}_{air,}(t)$ is the Relative Humidity (%) at the exterior context of BK Lab in time (t)

$\Delta RH^{Patio}_{air,\ SHD..BENEFITS}$ is the Relative Humidity (%) difference at Patio achieved with solar shading pergola and architectural form.

Table 21: Format of the data table for the T (°C) difference achieved at the patio with architectural form and solar shading pergola, including values for minimum, maximum, and average at the BK lab patio during the 48-hours experiment

Patio Shading: 	Winter	Transitional Season		Peak Summer		
	January	**March**	**April**	July	August	September
Min.						
Max.						
Average						

The air temperature (°C) benefits with use of bioclimatic actions of solar pergola, architectural form and orientation at BaityKool analyzed across the three meteorological periods: peak summer, winter and transitional season, presented with the format in Table 21. The positive values of Air Temperature (°C) indicate the reduction achieved with the action experiment scenarios at the patio, expressed in terms of the month's minimum (Min.), maximum (Max.), and average (Avg.) values in 6-hour differences for the 48-hour experiment.

3.6.3 Envelope performance for minimized heat transfer and temperature stability indoors

The envelope system plays a critical role in maintaining indoor thermal comfort with minimized reliance on the mechanical cooling system. The thermal insulation of the envelope system was tested for the potential temperature difference achieved indoors under passive conditions. The temperature difference between indoors with no solar shading for the glazing and the external lab site context is calculated using Eq. 11.

$$\Delta T^{Room}_{air,\ N,\ SHD} = \left(T^{Room,}_{air,\ N,\ SHD}(t) - T^{EXT\ ,}_{air,}\ (t) \right) \qquad \textit{Eq. (11)}$$

where

$T^{Room,}_{air,\ N,\ SHD}$ (t) is the Air Temperature (°C) at room with no solar shading in time (t)

$T^{EXT\ ,}_{air,}$ (t) is the Air Temperature (°C) at the exterior context of BK Lab in time (t)

$\Delta T^{Room}_{air,\ N,\ SHD}$ is the Air Temperature (°C) difference at Room achieved by the envelope system with no solar shading for the glazing.

The data was analyzed at the time of day when the maximum temperature difference occurs indoors, with no shading for openings, compared to the temperature difference achieved with solar shading for the glazed windows and doors.

Table 22: Format of the data table for the maximum air temperature (°C) difference achieved in 6-hour difference at indoors with solar shading at the BK lab during the experimental duration

t (Time)	Ext. Con. (T) Date/ Month	Room (T) with no SS Date/ Month	Diff (T) Room Date / Month (A)	Ext. Con. (T) on Exp. Date/ Month	(T) Exp. Room with SS Date/ Month	Diff (T) with SS on Date/ Month (B)	Diff (T) at Room achieved with SS: [(B)-(A)]

The indoor temperature stability of the prototype was analyzed to assess the consistency achieved by the envelope system and solar shading, as illustrated in the graphs.

3.6.5. Indoor Moisture Content

The direct way to measure indoor moisture content is through Absolute Humidity (AH). this indicates the actual amount of water vapor in the air, regardless of temperature. In contrast, RH depends on temperature because it represents the ratio of current moisture to the air's maximum moisture-holding capacity at a specific temperature. RH can change with temperature even if the actual moisture level stays the same. Human comfort and health issues, such as dry skin and respiratory problems, are more directly linked to AH than to RH. Monitoring AH helps ensure better moisture control to prevent problems like condensation, excessively dry air, or mold.

The ASHRAE Standard 55 [67] for thermal environmental conditions for human occupancy recommends a relative humidity (RH) between 30% and 60% and an indoor temperature of 20°C to 24 °C, suitable for home and office environments. This corresponds to absolute humidity (AH) values of 5 to 12 g/m³. The Absolute Humidity (AH) is calculated using the OMNI calculator for absolute humidity from relative humidity and air temperature.

$$AH = \frac{RH \times Ps}{Rw \times T \times 100} \qquad \textit{Eq.(12)}$$

where

RH is the Relative humidity

Ps is the Saturation vapor pressure, measured in pascal (Pa)

Rw is the 461.5 J/(kg·K) – Specific gas constant for water vapor

T is the Temperature, measured in °C

According to equation proposed by Wagner and Pruss, [90]the saturation vapor pressure of water at a given temperature T can be written as:

$$Ps = Pc \exp\left[Tc/T \left(a_1 r + + a_2 r^{1.5} + a_3 r^{3} + a_4 r^{3.5} + a_5 r^{4} + a_5 r^{7.5} \right) \right] \qquad \textit{Eq. (13)}$$

where

Pc is 22.064 MPa – Critical pressure for water

Tc is 647.096 K – Critical Temperature for water

a1, a2,.., a6 is Empirical constants

T is 1−T/Tc

Table 23: Format of Data table for AH at BK experimental zones in months of peak summer, winter & transitional season

AH (g / m3)	PEAK SUMMER, WINTER & TRANSITIONAL SEASON											
	MONTH				MONTH				MONTH			
	N - Ref		EXP - SS:RBB		N - Ref		EXP SS:RBB		N - Ref		EXP - SS:RBB	
Room/ Orientation	Ref. Room	Ref. Room	Room	Room.	Room	Room	Room	Room	Room	Room	Room	Room
Time (hrs.)	EAST	WEST	EAST	WEST	EAST	WEST	EAST	WEST	EAST	WEST	EAST	WEST
6:00												
12:00												

3.7 Chapter Summary

Chapter 3 outlines the experimental scenarios and sets, including the experiment period, duration, occupancy status of the living lab, and indoor environment conditions. The scenarios assess the potential for reducing solar heat gain and enabling natural cooling indoors under passive conditions using actions such as solar shading curtains, natural ventilation, night ventilation, and solar shading. The patio shading experiment explores the microclimate effect at the BK site, influenced by the architectural orientation and the solar shading pergola, compared to external air temperature. The experimental plan details actions across different seasons, focusing on peak summer, winter, and transitional periods. The solar shading experiments demonstrate the temperature reductions possible with solar shading curtains RBB, ETC, and ITC, by decreasing direct solar radiation on glazed windows and doors during peak summer. Natural ventilation experiments evaluate the impact of cross-ventilation during cool nights, utilizing diurnal temperature variations for passive cooling in winter and transitional seasons, thus reducing cooling energy use. Night ventilation and solar shading experiments during transitional periods assess the potential for passive thermal comfort at night, when exterior temperatures are lower, and for extending indoor comfort during the day with solar shading curtains. The patio shading experiments highlight the benefits of courtyard-based bioclimatic design strategies in summer, winter, and transitional periods. These scenarios examine the performance of an envelope system designed for extreme warm climates, where thermal mass acts as a thermal battery, absorbing heat during the day to keep the space cool and releasing it at night. Instrumentation tools, measurement parameters, protocols, and procedures are detailed for all experiments. The data analysis procedures, including equations used to evaluate

the impact of actions on indoor air temperature ($\Delta T_{air,\ ACTION\ Benefits}^{Room}$) and difference achieved in the relative humidity ($\Delta RH_{air,EXP}^{Room}$) at 6-hours interval with the action. The experiments of the Patio Shading evaluates the ($\Delta T_{air,\ SHD..BENEFITS}^{Patio}$) **and** ($\Delta RH_{air,\ SHD\ BENEFITS}^{Patio}$) with use of bioclimatic actions of solar pergola, architectural form and orientation at BaityKool analyzed across the three meteorological periods: peak summer, winter and transitional season. The envelope performance for minimized heat transfer and temperature stability indoors was analyzed to evaluate the potential temperature reduction benefits achieved indoors under passive conditions with minimized reliance on the mechanical cooling system. The evaluation of the action benefits between the varied scenarios for each experiment was performed according to the experiment plan. The experiments conducted have the data acquired with a time set of 15 minutes; the data collected have been compiled at 6-hour intervals (00h, 06h, 12h, 6h, etc.) throughout the 48 hours analyzed using model equations organized into tables and graphs addressing the research objectives.

Quick summary of Chapter 3

- Experimental Scenarios and Zone presented for the BaityKool living lab, presenting the experimental design for the actions using passive design strategies like solar shading, natural ventilation, night ventilation with solar shading, patio shading, and envelope performance to test the research objectives for optimized thermal comfort and minimize energy consumption.
- The experimental plan presented throughout the year, focusing on peak summer, winter, and transitional periods for the actions' benefits with bioclimatic strategies under passive conditions.
- The Solar shading experiments enabling the assessment of the benefit of solar shading curtains (RBB), (ETC), and (ITC), reducing solar heat gain for glazed windows and doors.
- The Natural ventilation experiments enable the assessment of the impact of benefits with cross ventilation during cooler nights.
- The combination of Night ventilation and solar shading experiments enables the assessment of the impact of solar shading to prolong the benefits of free cooling achieved at night during the transitional seasons with diurnal temperature range.

- The Patio shading experiment assesses the benefits of courtyard-based design in an extreme warm climate with microclimate differences achieved with bioclimatic strategies.
- The experiment scenarios across the peak summer, winter, and transitional periods enable the assessment of the envelope system designed for the extreme warm climate with the use of thermal mass to manage the indoor air temperature fluctuations.
- The instrumentation tools, measurement parameters, protocols, and procedures were described to gather information from them. The collected data were analyzed using model equations and organized into tables as discussed in Chapter 4, offering a detailed evaluation and analysis of this data, addressing the research objectives.

Chapter 4.

Experimental results and analysis

Chapter 4. Experimental results and analysis

4.1 Introduction

This chapter offers an overview of the experimental results and their analysis. It examines the effects of solar shading and natural ventilation, courtyard (patio) influence, and the intrinsic performance of the envelope. These factors are considered across three meteorological periods: peak summer, winter, and transitional season. The impact of the experimental scenarios for solar shading (SS), natural ventilation (Nat.V), and patio environment (Pat. SS) on the BK prototype is analyzed in relation to temperature and relative humidity dynamics in the relevant thermal zones.

The experimental results SS during the peak summer months of July, August, and September are presented, along with the overall air temperature difference achieved using the shading devices RBB, ETC, and ITC. By identifying the minimum, maximum, and average values of air temperature in the East- and West-oriented rooms of the BK lab, the potential for reducing air temperature through SS architectural interventions with RBB, ETC, and ITC is highlighted. Detailed analysis of SS performance during the summer months of the experimental period is provided through tables, graphs, and insights derived from the results. The natural ventilation (Nat.V) experimental results for the Winter season are also presented to illustrate the potential for air temperature reduction with architectural actions such as Day & Night Ventilation (DV + NV) in January, Night Ventilation (NV) in January and April, and Night Ventilation combined with solar shading (NV + SS) during the transitional months of March and April. By identifying the minimum, maximum, and average air temperature values in the east- and west-oriented rooms of the BK lab, these temperature reduction potentials are showcased. A detailed analysis of Nat.V performance during winter and transitional months is provided through tables, graphs, and interpretations of the results. Additionally, the patio environment demonstrates the air temperature difference between the patio and outside temperature, achieved through the architectural form and the solar shading pergola during summer. The performance results pertaining to the BaityKool envelope system's ability to minimize heat and mass transfer from exterior to interior are then presented and discussed.

4.2 Weather condition at BaityKool living Lab location during the experiment period

The psychrometric simulation graph maps the climate data by months for the annual weather data at the BaityKool living lab location, TSC, Dubai, UAE, during the experiment period 2023-2024.

The graph in Fig. 84 shows the period from December to February fall in the comfort zone. The months November to March can incorporate passive 'Natural Ventilation' strategies. The months November to April can use Mass-Cooling, and October and May can use 'Mass-Cooling and Night Ventilation'. The four months June to September require 'Air-conditioning and Dehumidification' for thermal comfort indoors.

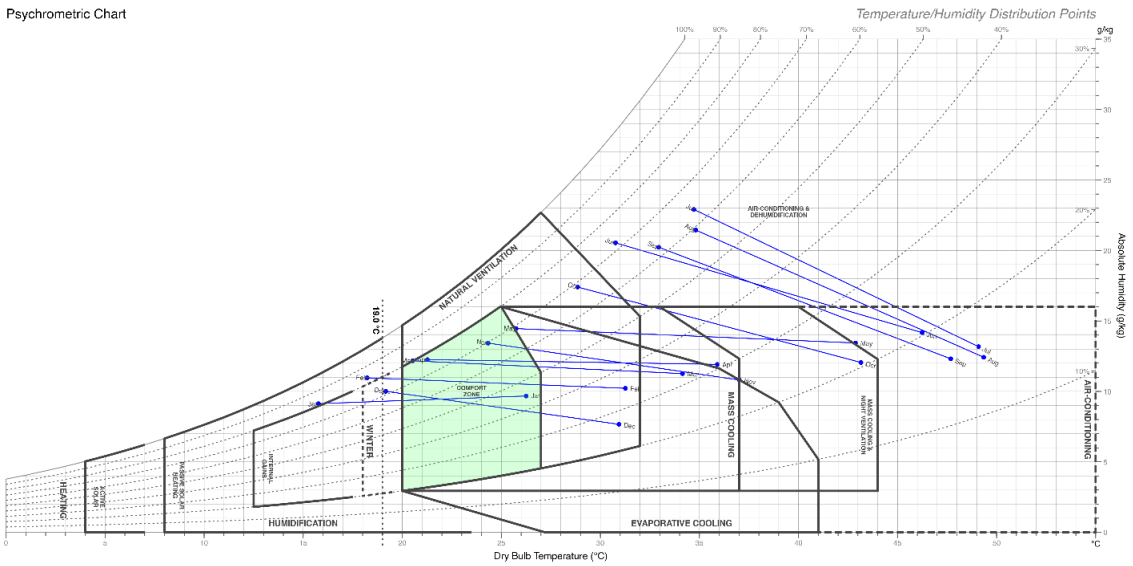


Figure 84: Psychrometric chart simulation for the weather data at BaityKool living lab location TSC, Dubai, UAE (Source: Author)

The Psychrometric chart [46] helps assess and validate the bioclimatic decisions of the BaityKool prototype design for the extreme warm climate. The impact indicators for the actions on mobile bioclimatic systems, including solar shading, natural ventilation, night ventilation with solar shading, and patio solar shading, align with the strategies suggested in the Psychrometric chart, as indicated in section 3.3.5, Fig. 77. The graphical representation for the experiments with impact action at the BaityKool living lab is as shown Fig.85.



(a) (b) (c)

Figure 85:Graphical representation for (a) Solar Shading, (b)Natural Ventilation, (c) Patio Solar Shading

4.2.1 Experimental analysis of Solar Shading indoor effects

This session presents the analysis of data collected during the experiments, which are organized into five parts to provide an overall perspective on the effects of bioclimatic actions, from the local level of individual rooms in the experiment zones to the broader level.

4.2.1 (i) An overall view of indoor air temperature reduction potentials using SS (RBB, ETC, ITC) for the summer months

The experimental results for the solar shading set with shading devices RBB, ETC, and ITC are presented for the summer season in Table 24. The comparison of indoor air Temperature T (°C) impact with Action: Solar Shading at experiments associated with these shading devices is shown for the experimental months of July, August, and September at the BaityKool prototype. The Eq. 3 used to find the ($\Delta T^{Room}_{air,\ ACTION\ Benefits}$), air Temperature reduction potential with active bioclimatic action of Solar Shading Curtain: RBB, ETC & ITC during the 48-hour experiment. The overall potential reductions in indoor air temperature between the experimental zone-oriented East, with the living room, and the experimental zone oriented west, with the bedroom, are expressed in terms of the month's minimum (Min.), maximum (Max.), and average (Avg.) values compiled in Table 24.

Table 24: The indoor air temperature reduction $\Delta T^{Room}_{air,\ ACTION\ Benefits}$ (cf. Section 3.6.1, Eq. 4) during peak summer, between use and no-use of Solar Shading Curtain (SSC): RBB, ETC, and ITC Solar Shading types (cf. Section 3.3.1)

Months	**Exp. SSC**	**RBB** (°C)		**ETC** (°C)		**ITC** (°C)	
	Room Orientation	EAST room	WEST room	EAST room	WEST room	EAST room	WEST room
July	Min	7.3	6.3	2.5	1.3	2.2	2.6
	Max	8.8	8.3	6.9	6.0	4.0	4.1
	Avg.	8.1	7.3	4.7	3.6	3.1	3.3
Aug.	Min	3.3	4.5	0.4	0.5	0.3	0.5
	Max	7.5	6.1	1.9	1.6	1.3	1.5
	Avg.	5.4	5.3	1.2	1.1	0.8	1.0
Sept.	Min	2.4	2.5	0.6	0.8	0.3	0.3
	Max	3.4	3.4	2.8	2.9	0.8	0.9
	Avg.	2.9	2.9	1.7	1.8	0.6	0.6

Table 24 demonstrates that the Solar Shading Curtain Roller Blind Blackout (RBB) can significantly reduce indoor air temperatures, with an average decrease of 8.10°C in July, 5.48°C in August, and 2.95°C in September compared to ETC & ITC.

The sky was moderately cloudy in August due to cloud seeding in Dubai, which caused artificial rain. As a result, the findings indicate an average indoor air temperature reduction of 4°C with SS: RBB and a 1°C reduction with SS: ETC and ITC, mainly due to decreased solar radiation indoors through glazed areas caused by cloud cover from cloud seeding. Nonetheless, high radiant heat was experienced outside from the surrounding areas of the building and the heat island effect, with external temperatures ranging from 33°C to 51.10°C.

In September, the sky was also cloudy due to induced cloud seeding aimed at bringing rain to help combat the rising temperatures in Dubai. As a result, the SS: RBB showed an average reduction of 3 °C, while SS: ETC and ITC indicated only a 1 °C decrease indoors. The outdoor temperatures at the exteriors in September ranged from 30.6 to 45.10 °C.

Between the East and West-oriented rooms, the difference in indoor air temperature reduction impact with Action: Solar Shading at experiments was less than 1°C with solar shading curtains. A more detailed understanding of the impact of solar shading RBB on indoor air temperature based on orientation is discussed in Section 4.2.1 (ii) for the temperature fluctuations over 6-hour intervals during a 48-hour continuous experiment, and Section 4.2.1 (iii) shows the difference between the use (experiment SS) and no use (reference) of these shading devices.

The data in Table 24 show a potential reduction in indoor air temperature (°C) with the use of Solar Shading RBB by 8°C, ETC by 3-4°C, and ITC by 3°C, with effectiveness observed during sunny periods. When using solar shading RBB, the indoor air temperature at BaityKool ranges from 29°C to 31°C, while the outdoor temperature was 46°C to 48°C. The Solar Shading RBB is fixed outside the prototype's windows (refer to Fig. 69 (a)), which blocks sunlight before it reaches the glass. This prevents solar radiation from warming the glass, which would otherwise transfer heat inside. By stopping heat outside the glazed windows, less thermal energy enters the room, helping keep it cooler.

The Solar Shading ETC & ITC, being translucent (refer to Fig. 69 (b) & (c)), allows partial shading to be less effective than RBB because the translucent curtain permits sunlight to pass through the glazed windows and heat the air inside. The incoming radiation warms the indoor air. The ITC, being fixed from inside the glazed windows, can cause heat to be trapped between the window and the curtain, leading to an increase in indoor temperature. Using solar shading helped decrease the

operating time of the air conditioner required for thermal comfort, leading to energy savings by reducing the cooling load.

4.2.1 (ii) Potential temperature reduction using Solar Shading Curtain (RBB, ETC, and ITC) with Bioclimatic action during the 48-hour.

The potential indoor air temperature T (°C) impact with Action: Solar Shading using RBB, ETC, and ITC for the experiments (refer to Section 3.3.1, Fig. 70, Table 11 & 12) is presented separately by months, Table 25 for July, Table 26 for August, and Table 27 for September. The data to analyze the benefits of the solar shading devices is compiled at 6-hour intervals (00h, 06h, 12h, 6h, etc.) throughout the 48-hour experiment. The Eq.2 used to find the temperature difference achieved with the experiment ($\Delta T_{air,\mathrm{EXP}}^{Room}$), Eq. 3 to find the indoor air temperature °C difference with No Action at Experiment as baseline reference ($\Delta T_{air,\mathrm{REF}}^{Room}$). The Action benefits are the difference between the $\Delta T air, \mathrm{EXP} Room$ and ($\Delta T air, \mathrm{REF} Room$) calculated with Eq.4. The comparison between the East- and West-oriented rooms of the BaityKool living lab is presented with values for day 1 (24 hours) and day 2 (24 hours). The Action benefits show the potential indoor air temperature T (°C) reduction achieved using the solar shading curtain within 24 hours, along with the average temperature reduction benefits achieved by the envelope system and Thermal Inertia advantages.

- **Results of the 48-hour Solar Shading Curtain experiment conducted in July**

In July 2023 in Dubai, the sunrise was at 5:40 am, and the sunset was at 7:10 pm. The solar shading process continued until 9.00 pm during the experiment, with data collected and analyzed at 6-hour intervals. Table 25 shows higher temperature difference observed at night 0.00 hours and early morning 6.00 hours with SS: RBB making an air temperature reduction of 10°C. There is a consistent 8°C to 9°C reduction in the indoor air temperature 18 hours (from 6.00 am to 12.00 am). The indoor environment of the BK prototype during peak summer months in July, with SS: RBB, shows an average temperature reduction of -8 °C. Meanwhile, SS: ETC demonstrates an average reduction of -4 °C, and SS: ITC shows an average reduction of -3 °C. The composite layered wall of the envelope system and its thermal inertia help manage thermal delay and the temperature reduction range, ensuring indoor comfort during summer and preventing overheating. When the exterior temperature rises to 48 °C, the indoor temperature remains at 29-30 °C at noon, using SS: RBB. (Refer Table 28 for the air temperature difference during experiment.)

Table 25: The Potential indoor air temperature reduction $\Delta T^{Room}_{air,\ ACTION\ Benefits}$ *(cf. section 3.6.1, Eq.4) at 6-hour intervals for 48 hours in July, between use and no-use of Solar Shading Curtain (SSC): RBB, ETC, and ITC Solar Shading types (cf. Section 3.3.1)*

SOLAR SHADING CURTAIN / MONTH & YEAR			**Exp. SS : RBB-JULY 23**			**Exp. SS : ETC-JULY 23**			**Exp. SS : ITC JULY 23**		
ORIENTATION			East		West	East		West	East		West
Action		Solar Shading (SS)	**Liv. T (°C)**	**Kit T (°C)**	BRm T (°C)	**Liv. T (°C)**	**Kit T (°C)**	**BRm T (°C)**	**Liv. T (°C)**	**Kit T (°C)**	**BRm T (°C)**
T Benefit SS: RBB, ETC, ITC	Solar Shading Period	6:00	-9	-8	-8	0	0	1	No ITC in Liv.	-5	-5
		12:00	-8	-7	-6	-3	-2	-1		0	0
		18:00	-9	-8	-8	-4	-4	-3		-4	-4
	Night	0:00	-10	-10	-9	-4	-3	-3		-4	-4
	Solar Shading Period	6:00	-11	-11	-11	-6	-6	-5		-4	-5
		12:00	-8	-7	-7	-4	-4	-5		-4	-4
		18:00	-7	-8	-7	-7	-7	-6		-2	-3
	Night	0:00	-4	-4	-4	-5	-5	-4		-2	-2
	Early Morning	6:00	0	0	-1	-4	-5	-4		1	1
6.00 to 18.00 **day 1**		Max	-9	-8	-8	-4	-4	-3		-5	-5
		Min	-8	-7	-6	0	0	1		0	0
		Average	-8	-8	-7	-3	-3	-2		-2	-2
6.00 to 18.00 **day 2**		Max	-11	-11	-11	-7	-7	-6		-4	-5
		Min	-7	-7	-7	-4	-4	-5		-2	-3
		Average	-8	-7	-7	-5	-6	-6		-3	-3
Thermal Inertia Benefit			-10	-10	-9	-4	-3	-3		-4	-4
Average of 2 days			**-8**	**-8**	**-7**	**-4**	**-4**	**-4**	**0**	**-3**	**-3**

Note: **(-Ve)** indicated the potential indoor air temperature °C reduction, **(+Ve)** indicated the potential indoor air temperature °C increase

- **Results of the 48-hour Solar Shading Curtain experiment conducted in August**

In August 2023, the sunrise was at 5:40 am and the sunset was at 7:00 pm. The solar shading was maintained until 9 pm during the experiment period, and data was analyzed at six-hour intervals. The indoor air temperature (°C) impact with Action: Solar Shading using RBB, ETC, and ITC with the maximum, minimum, and average potential reduction is summarized in Table 26.

During August, the peak summer month, indoor conditions in the BK prototype with SS: RBB show an average potential indoor air temperature reduction of -4°C, while SS: ETC and ITC have an average potential reduction of 0°C. The lower indoor temperature reduction potential in August is attributed to the outdoor cloudy weather, which was induced by cloud seeding in Dubai to encourage rain, as temperatures reached up to 50 °C. The outdoor environment was extremely hot,

with high temperatures and a cloudy sky that reduced direct sunlight. The indoor air temperature at the BaityKool prototype with SS: RBB ranged from 28°C - 29°C, compared to outdoor temperatures of 49.5°C - 51 °C, creating a temperature difference of 22 °C with RBB.

Table 26: The Potential indoor air temperature reduction $\Delta T^{Room}_{air,\ ACTION\ Benefits}$ *(cf. section 3.6.1, Eq 2, Eq3 & Eq.4) at 6 hours intervals for 48 hours in August, between use and no-use of Solar Shading Curtain (SSC): RBB, ETC, and ITC Solar Shading types (cf. Section 3.3.1)*

SOLAR SHADING CURTAIN / MONTH & YEAR			**Exp. SS : RBB Aug 23**			**Exp. SS : ETC Aug. Sept 23**			**Exp. SS : ITC Sept 23**		
ORIENTATION			East		West	East		West	East		West
Action		Solar Shading (SS)	**Liv. T (°C)**	**Kit T (°C)**	**BRm T (°C)**	**Liv. T (°C)**	**Kit T (°C)**	**BRm T (°C)**	**Liv. T (°C)**	**Kit T (°C)**	**BRm T (°C)**
T Benefit SS: RBB, ETC, ITC	Solar Shading Period	6:00	-3	-3	-3	0	0	0	No ITC in Liv.	-1	-1
		12:00	-4	-4	-5	0	0	1		-1	-2
		18:00	0	0	-1	-2	-2	-2		0	-1
	Night	0:00	-2	-2	-2	-1	-1	-1		0	-1
	Solar Shading Period	6:00	-5	-2	-2	-1	-1	-1		-1	-1
		12:00	-8	-6	-6	2	2	2		-5	-5
		18:00	-3	-5	-5	2	1	1		0	0
	Night	0:00	-3	-4	-4	0	-1	-1		0	0
	Early Morning	6:00	-3	-2	-2	0	0	0		-2	-2
6.00 to 18.00 **day 1**		Max	-4	-4	-5	-2	-2	-2		-1	-2
		Min	0	0	-1	0	0	1		0	-1
		Average	-2	-2	-3	-1	-1	-1		-1	-1
6.00 to 18.00 **day 2**		Max	-8	-6	-6	-1	-1	-1		-5	-5
		Min	-3	-2	-2	2	2	2		0	0
		Average	-5	-5	-6	2	2	1		-2	-3
Thermal Inertia Benefit			-2	-2	-2	-1	-1	-1		0	-1
Average of 2 days			-4	-4	-4	1	1	0		-2	-2

Note:**(-Ve)** indicated the potential indoor air temperature °C reduction, **(+Ve)** indicated the potential indoor air temperature °C increase

- **Results of the 48-hour Solar Shading Curtain experiment conducted in September**

In September 2023, sunrise was at 5:30 am and sunset at 7:13 pm. The solar shading stayed in place until 9 pm during the experiment, and data were collected every 6 hours. Table 27 shows the maximum, minimum, and average potential impact of solar shading for temperature reduction.

The average temperature reduction indicates that indoor temperatures decrease less in September with RBB, ETC, and ITC compared to July. During the peak summer month of September, the BaityKool prototype's indoor conditions with SS: RBB show an average temperature reduction of -3°C. In contrast, SS: ETC and ITC have an average potential temperature reduction of 0°C. This is due to cloudy weather conditions at the external site, which was caused by cloud seeding in Dubai to induce rain. The SS displayed a potential temperature reduction ranging from 1°C to 3°C on a cloudy day.

Table 27: The Potential indoor air temperature reduction $\Delta T^{Room}_{air,\ ACTION\ Benefits}$ *(cf. section 3.6.1, Eq 1, Eq2 & Eq.3) at 6 hours intervals for 48 hours (cf. Section 3.6.1, Eq. 3) in September, between use and no-use of Solar Shading Curtain (SSC): RBB, ETC, and ITC Solar Shading types (cf. Section 3.3.1)*

SOLAR SHADING CURTAIN / MONTH & YEAR			**Exp. SS : RBB-SEPT 23**			**Exp. SS : ETC-SEPT 23**			**Exp. SS : ITC OCT 23**		
ORIENTATION			East		West	East		West	East		West
Action		Solar Shading (SS)	**Liv. T (°C)**	**Kit T (°C)**	**BRm T (°C)**	**Liv. T (°C)**	**Kit T (°C)**	**BRm T (°C)**	**Liv. T (°C)**	**Kit T (°C)**	**BRm T (°C)**
T Benefit SS: RBB, ETC, ITC	Solar Shading Period	6:00	1	1	1	-4	-4	-4	No ITC in Liv.	1	1
		12:00	-3	-3	-3	-3	-3	-3		-5	-5
		18:00	-2	-2	-3	-1	-1	-1		-1	-1
	Night	0:00	-2	-3	-3	0	0	0		1	1
	Solar Shading Period	6:00	-4	-4	-4	1	1	1		1	1
		12:00	-3	-3	-2	1	1	1		1	1
		18:00	-3	-3	-3	-1	-1	-1		0	0
	Night	0:00	-2	-2	-2	1	1	1		1	1
	Early Morning	6:00	-2	-3	-2	0	0	0		0	1
6.00 to 18.00 **day 1**		Max	-3	-3	-3	-4	-4	-4		-5	-5
		Min	1	1	1	-1	-1	-1		1	1
		Average	-3	-3	-3	-2	-2	-2		-3	-3
6.00 to 18.00 **day 2**		Max	-4	-4	-4	-1	-1	-1		0	0
		Min	-3	-3	-2	1	1	1		1	1
		Average	-3	-3	-3	0	0	0		0	0
Thermal Inertia Benefit			-2	-3	-3	0	0	0		1	1
Average of 2 days			-3	-3	-3	-1	-1	-1		-1	-1

Note: **(-Ve)** indicated the potential indoor air temperature °C reduction, **(+Ve)** indicated the potential indoor air temperature °C increase

4.2.1 (iii) Analysis of solar shading performance for RBB with temperature measured at 1-hour intervals for 48 hours during the experiment.

The data analysis of Solar Shading (SS) performance for RBB in July, August, and September, year 2023 is presented, highlighting the differences in indoor air temperature, T (°C), between the baseline reference (Ref.) experiment without solar shading using Eq. 3 and the experimental (Exp.) scenario with a solar shading curtain (SSC) using Eq. 2. The Eq. 4 used to calculate the indoor air Temperature T (°C) impact with Action Solar Shading at Experiment. Data collated for the indoor zones on the East with living (Liv.) and the West with bedroom (BRm.) show the effects of solar shading based on orientation. The temperature variations during the 48-hour experiment were examined at 6-hour intervals on the baseline Ref. & Exp. SS: RBB days, presented in Table 28 for July, Table 29 for August, and Table 30 for September, and graphs for respective months comparing the temperature (°C) in the East- and West-oriented rooms of the experimental zones.

The Table 28, (Refer Appendix D) shows data collected every 6 hours (00h am, 06h am, 12h am, 6h pm, etc.) over 48 hours during the Solar Shading RBB experiment in a living room facing east (see Section 3.3.1, Figure 70, Table 11 & 12). The experiment took place during peak summer months July, August, and September. Its purpose is to analyze potential indoor air temperature reductions (°C) and the effect of using or not using the solar shading curtain RBB. The Table 28 (Refer Appendix D) compares indoor air temperature differences with outdoor temperatures, using solar shading RBB (EXP. SS: RBB) with Eq. 2, and no shading, labeled as no action (REF.), with Eq. 3. The benefits of solar shading with RBB in the living room and its impact on indoor air temperature (°C) are calculated using Eq. 4, which considers the difference in indoor temperature during the experiment relative to the baseline reference. The comparison between the reference (REF) and experiment (EXP) is presented separately for July, August and September in Table and Graphs. A negative value of indoor air temperature (°C) in the table indicates a drop in indoor air temperature, while a positive value indicates a rise.

- **Indoor air Temperature (°C) Action Benefits with Solar Shading: RBB at 1 hours interval in July 2023**

During the peak summer period at the BaityKool living lab location, high solar radiation is recorded in July 2023, with exterior temperatures reaching as high as 46-48°C. Meanwhile, indoor air temperatures stayed between 29-30°C from 6 am to 6 pm (a 12-hour span) under passive conditions. The external temperature in July during the experiment days ranged from 31 to 48°C.

Rooms with glazed openings facing outside and without solar shading curtains, RBB had temperatures between 33 and 37°C between 6 am and 12 pm. The use of solar shading RBB with reflective blackout during the experiment lowered indoor air temperatures to between 29 and 30°C without air conditioning, with one occupant living and working throughout the experiment days at the BaityKool living lab.

Fig. 86 shows the reference day for the east-oriented living space, revealing a temperature difference of 9.5°C to 18°C at noon when comparing the use and non-use of solar shading RBB in July. An indoor air temperature drop of 17°C to 18°C is achieved with Solar Shading RBB at noon on both days of the experiment. Compared to rising external temperatures without solar shading, the building envelope system could maintain a temperature difference of 9°C despite increasing outdoor temperatures. Under passive conditions without air conditioning, the living space maintained a temperature between 33 and 37°C during the 48-hour baseline reference period as seen in Fig. 86. The living space with Solar Shading RBB could keep the indoor air temperature in the range of 29°C to 34°C as seen in Fig.87. Even with a single occupancy during the 48 hours' experiment duration a significant reduction of 8°C in indoor air temperature was observed in the east-oriented living area from 6 am to 6 pm. Solar shading Curtain RBB could effectively block direct solar radiation from the external glazed areas. (Refer Table 28 in Appendix D)

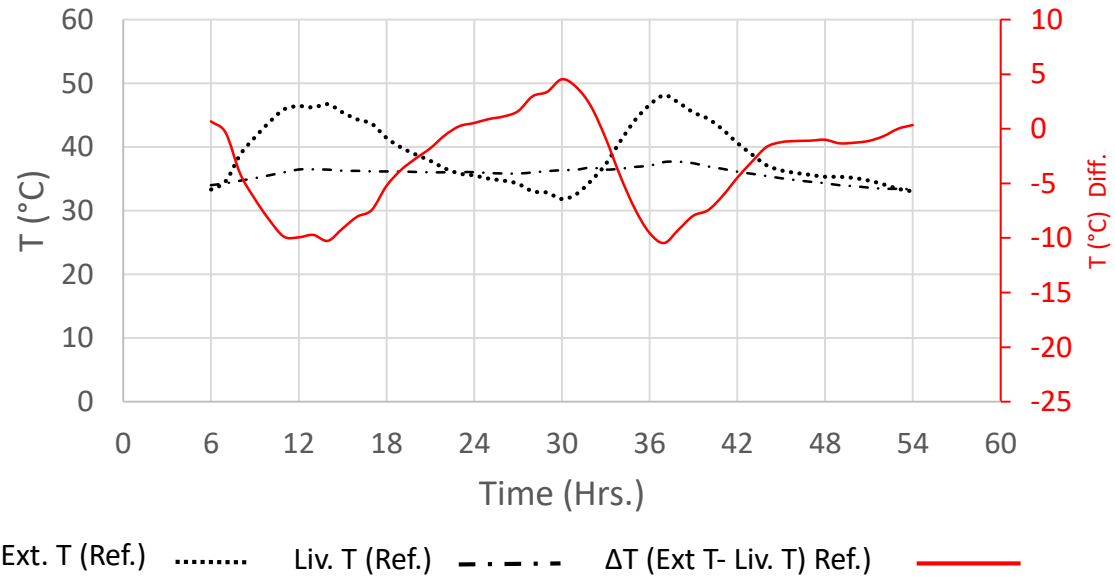


Figure 86: Comparison of indoor air temperature (°C) in Living (Liv.) with external air temperature on Ref. day, T Difference between Ext. & Liv. (Ref)

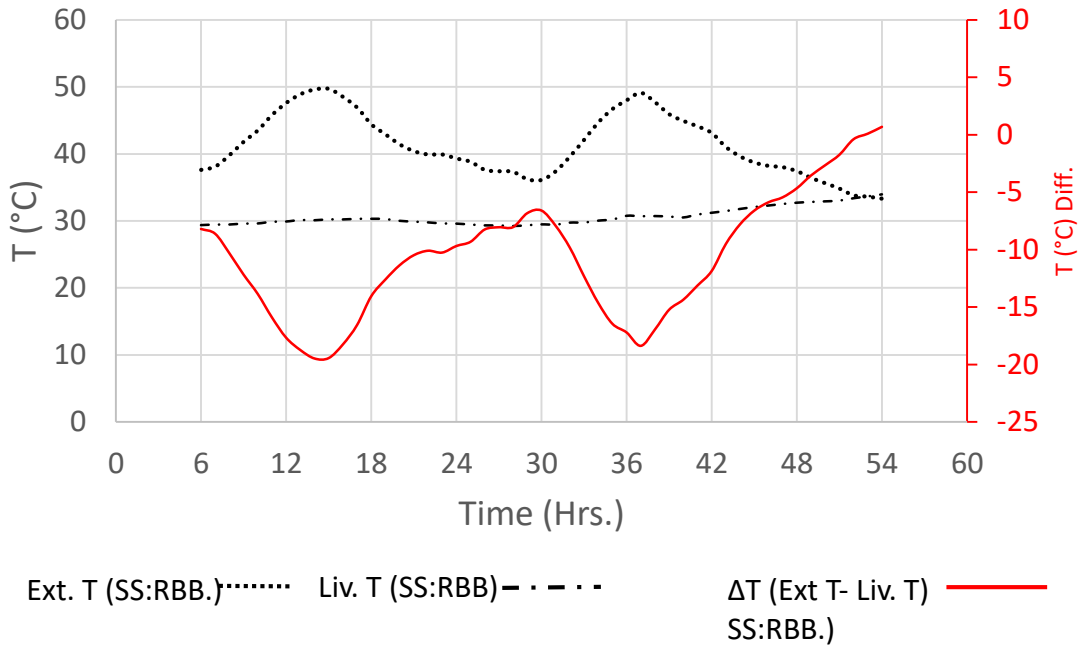


Figure 87: Comparison of indoor air temperature (°C) in Living (Liv.) with external air temperature on Exp. SS:RBB day , T Difference between Ext. & Liv. (SS:RBB)

Fig. 86 and 87 display the graph comparing the Reference and the action Experiment SS: RBB. On 15th July 2023 and 17th July 2023, data were collected over 48 hours with six 6-hour intervals. A heatwave occurred at noon, with temperatures rising to 48°C, and an increase in temperature was observed at the patio. A temperature drop is noted when using Solar Shading RBB compared to the reference experiment without solar shading. The pattern of temperature variation between the reference and Experiment SS: RBB in the living area shows a slight increase of less than 1°C over 12 hours on day 1, as seen in Fig. 87. On the second day of the Solar Shading: RBB experiment, the temperature rises by 4.5°C during the next 12 hours.

This increase is due to heat trapped in the room with all doors and windows closed during the 48 hours. The indoor temperature shows a difference of 17°C recorded at noon on both days with Solar Shading RBB. A clear difference in indoor air temperature lines is observed between Fig. 86 and Fig. 87, illustrating the benefits of using solar shading RBB compared to external temperature increases. Day one of the experiment shows consistent indoor air temperatures due to the thermal inertia of the clay tile lining the walls of the envelope system and the concrete floor. The envelope system delays heat transfer, absorbs and stores heat during the day, and releases it at night.

- **Indoor air Temperature (°C) Action Benefits with Solar Shading: RBB at 6 hours interval in August 2023**

The external temperature in August 2023 ranged from 30°C to 46°C as seen in Table 29, (Refer Appendix D). The rooms facing outside, which had glazed openings and no shading systems, recorded a temperature range of 27°C to 31°C. With the use of solar shading RBB, the temperature stayed steady between 27°C and 29°C during the experiment.

The Fig. 89, (Refer Table 29, Appendix D) shows external temperature at 12 noon on the first day of the RBB experiment reached 51°C (August 25, 2023), and 49.4°C on the second day. The indoor temperature in the living area with the RBB shading system at 12 noon on both days remained between 27°C and 28°C, creating a temperature difference of 22°C between the outdoor and indoor environments. The RBB experiment in August showed the potential to lower indoor air temperatures by 8°C under passive conditions without using air conditioning. An average reduction of 4°C was observed during the two-day experiment.

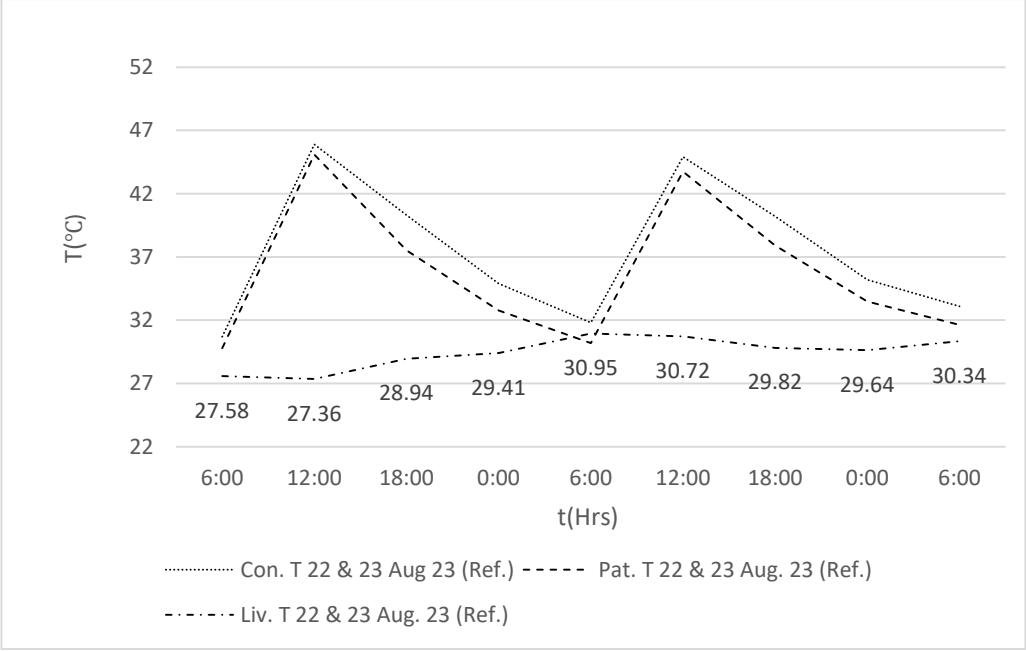


Figure 88: Comparison of indoor air temperature (°C) in Living (Liv.) with external and Patio (Pat.) air temperature on Ref. day in August

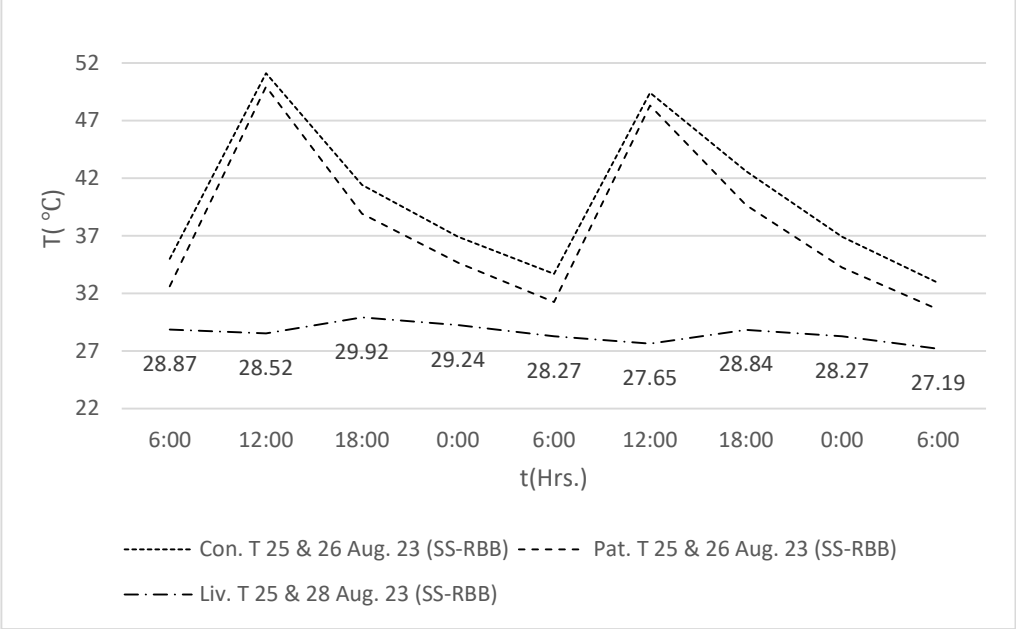


Figure 89: Comparison of indoor air temperature (°C) in Living (Liv.) with external and Patio (Pat.) air temperature on Exp. SS: RBB day in August

Fig. 88 and 89 show the graph over 48 hours comparing the Reference and action experiments. Solar Shading: RBB. In August, the temperature reached 51 °C on the first day of the experiment and then decreased to 49 °C on the second day. A difference is observed in the indoor temperature of the east-facing living space when using SS: RBB. There is a 3 °C increase without SS, while a steady temperature ranges of 27-28 °C is maintained with Solar Shading: RBB. Indoors, a temperature drop occurs with the use of SS: RBB compared to the Reference experiment without solar shading.

A temperature decrease is noted at noon on both days of the solar shading experiment, caused by the thermal inertia of the envelope system and floor- compare the temperature lines in Fig. 88 and Fig. 89 with and without solar shading. The temperature line shows an increasing pattern without shading because the glazing partially traps long-wave infrared radiation emitted by heated indoor surfaces. Additionally, the enclosed indoor space warms up over time, resulting in higher indoor air temperatures, as shown in Figure 88 with no solar shading. (Refer Table 29, Appendix D)

- **Indoor air Temperature (°C) Action Benefits with Solar Shading: RBB at 6 hours interval in September 2023**

The Table 30, (Refer Appendix D) shows external temperature in September as in ranged from 30 to 45°C, while in October 2023, it ranged from 28°C to 45°C during the first ten days of the month, marking the start of the transitional season as temperatures decreased to 25°C to 35°C.

The external rooms with glazed openings and no solar shading had temperatures ranging from 30°C to 32°C. Using solar shading and reflective RBB during the experiment resulted in a temperature drop of 28 to 30°C, without the use of air conditioning and with no occupancy on the experimental days, despite the exterior temperature rising to 47°C. Table 30, (Refer Appendix D) compares the reference and experimental days in the living area, showing the indoor air temperature difference achieved with solar shading/RBB, resulting in a 3°C reduction.

The building envelope system demonstrates the ability to maintain a consistent temperature of 28°C to 29°C when using solar shading and reflective RBB as seen in Fig. 91. A temperature increase of 2°C is observed without solar shading. A steady temperature of around 29°C in the living area is also shown in the graph in Fig. 91 at the 48-hour interval under passive conditions.

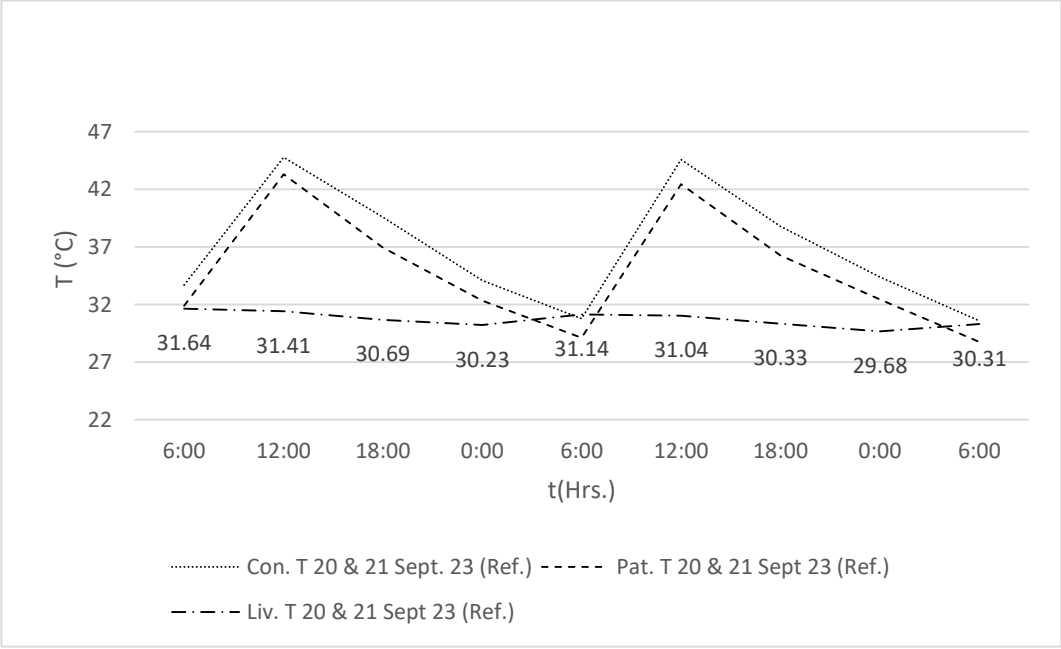


Figure 90: Comparison of indoor air temperature (°C) in Living (Liv.) with external and Patio (Pat.) air temperature on Ref. day in September

Fig. 90 and 91 display the graphs for 48 hours, comparing the reference with the action experiment Solar Shading RBB in September. The indoor air temperature on the reference day ranged from 30°C to 32°C, while the outdoor temperature reached 44.8°C at noon on both days of the reference experiment. A 3°C difference in indoor temperature is observed in the east-oriented living area using Solar Shading RBB on the experimental day, when the external temperature rose to 46.6°C.

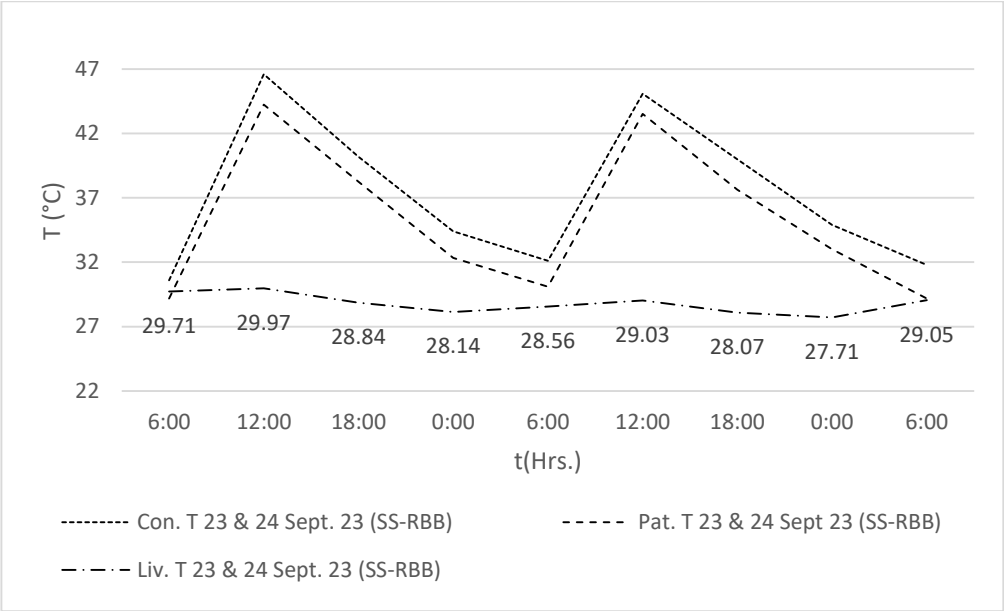


Figure 91: Comparison of indoor air temperature (°C) in Living (Liv.). with external and Patio (Pat.) air temperature on Exp. SS: RBB. day in September

A consistent temperature range of 28°C to 29°C is maintained under passive conditions with Solar Shading RBB. Cloud seeding was conducted in Dubai to induce rain, as temperatures reached up to 50°C. The outdoor environment was extremely warm, with high temperatures and a cloudy sky that reduced direct sunlight. Still, a temperature drop is noted indoors when using Solar Shading RBB compared to the reference experiment with no Solar Shading. This demonstrates the minimum temperature reduction potential on a cloudy day with extremely high temperatures.

4.2.1 (iv) Analysis of fluctuations in temperature (T) and relative humidity (RH) under reference and experimental conditions. SS: RBB days for East- and West-oriented rooms.

The data analysis presents indoor air temperature T(°C) fluctuations at set intervals of 6-hours with Action Solar Shading (SS) performance for RBB in July, August, and September in year 2023. . Eq. 5 is used to determine air temperature fluctuation (°C) over a 6-hour interval as the reference

with no action. Eq. 6 is used to calculate the air temperature fluctuation (°C) during the experiment over a 6-hour interval, achieved through active bioclimatic action. The fluctuations in indoor relative humidity (RH%) at set intervals with action during the experiment are calculated using Eq. 8 for the reference Relative Humidity fluctuation (%) over a 6-hour interval. Eq. 7 is used to determine the Relative Humidity fluctuation (%) during the experiment over a 6-hour interval.

The tables and graphs compare the temperature (°C) in the East- and West-oriented rooms of the experimental zones. Table 31 corresponds to July, Table 32 to August, and Table 33 to September. The analyzed data for the indoor zones on the East oriented living and the West oriented bedroom demonstrate the effects of solar shading based on orientation. The comparison of the computed temperature fluctuations can be interpreted with the (+Ve) values, which indicate a rise in temperature in (°C), with higher values than the previous hourly interval, and (-Ve) which indicates a decrease in temperature, with lower values than the last hourly interval. The data compilation suggests the rate of air temperature fluctuations (T) in the East- and West-oriented rooms of the BK living lab over the 48-hour experiment.

- **Indoor air temperature fluctuations in 6-hour interval regarding East-oriented living (Liv.) and West-oriented bedroom (BRm.) on reference days without shading and experimental days with SS: RBB in July 2023**

Fig. 92 shows temperature fluctuations of 2.4 °C over six hours from 6 am to 12 noon on Reference Day 1, with no solar shading for the east-facing living room and west-facing bedroom. In contrast, the temperature fluctuation is less than 1 °C during the same period on Day 1 with Experimental SS: RBB as seen in Fig. 93, due to the blocking of direct solar rays from the glazed windows and doors. The temperature variation in the east- and west-facing rooms with SS: RBB is reduced to less than 0.5 °C. At midnight, the temperature drops below the evening reading at 6 am, coinciding with a decrease in external temperature for both Reference and Experimental Days. A stable temperature is observed in the east- and west-facing rooms on both days, thanks to the thermal inertia of the envelope system and concrete floor. On Day 2 with Experimental SS: RBB, the temperature rises because an occupant in the lab opened the bedroom door to access the patio. Additionally, exterior temperatures on 15th and 16th July 2023 reached 47-48 °C, contributing to temperature fluctuations during the experimental day with solar shading. (Refer Table 31, Appendix D).

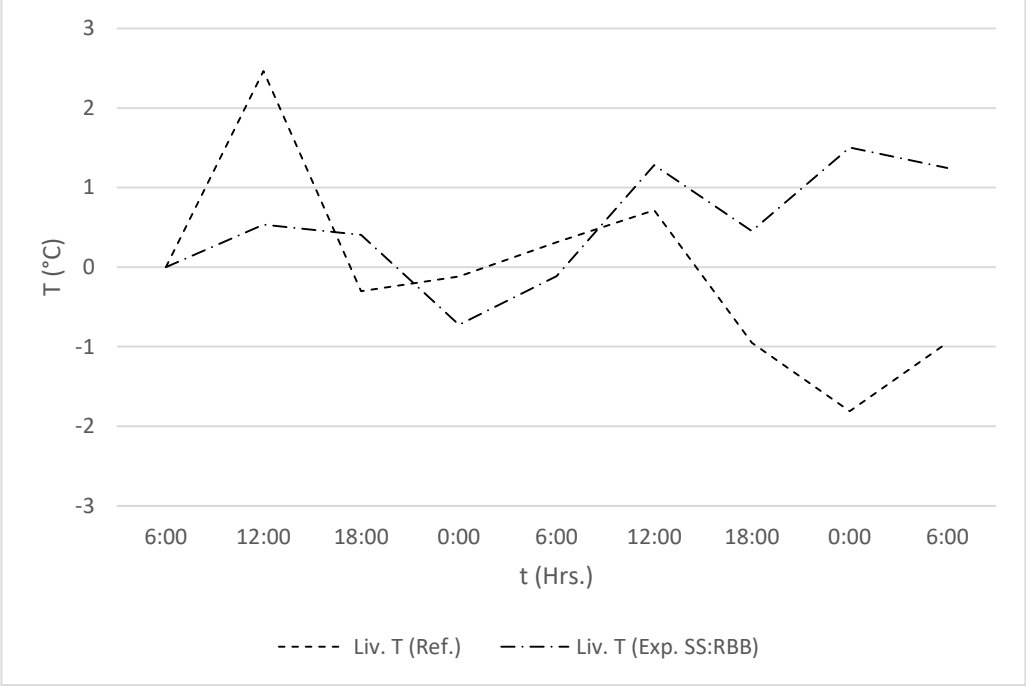


Figure 92: Indoor Air temperature fluctuations in 6- hour intervals at the Liv. (Ref.) & Liv. Exp. SS: RBB in July

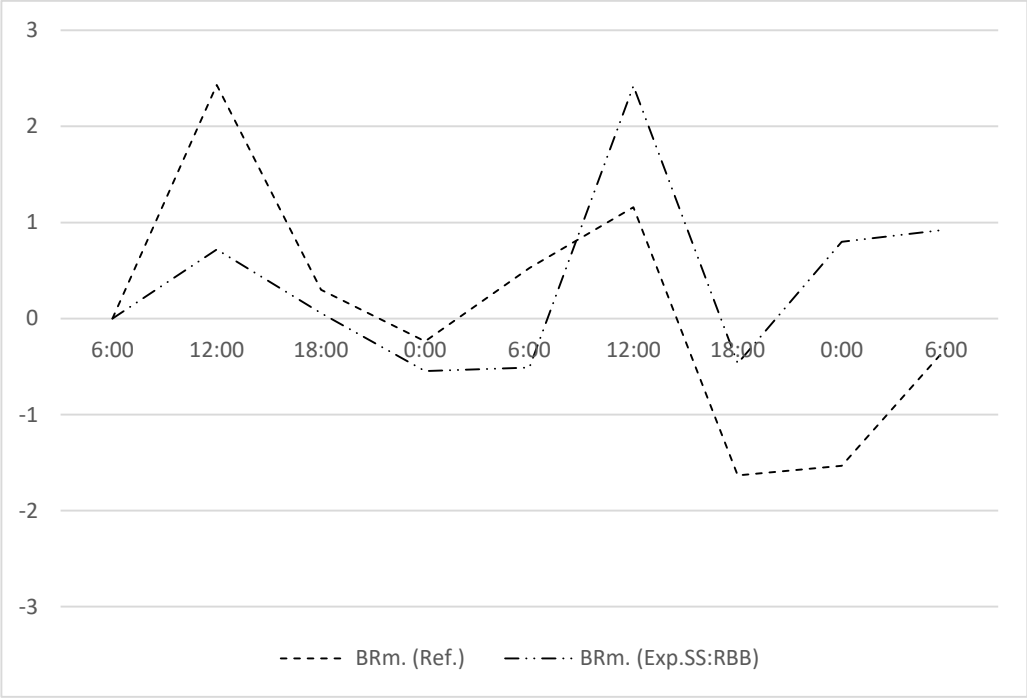


Figure 93: Indoor Air temperature fluctuations in 6-hour intervals at the BRm. (Ref.) & Liv. Exp. SS: RBB in July

Fig. 92 shows the graph of temperature fluctuations for the Reference and Experimental RBB in the east-facing living space during July. Fig. 93 presents the graph of temperature fluctuations for the Reference and Experimental RBB in the west-facing bedroom in July 2023. The graphs clearly show consistent temperatures, with a fluctuation range of 1°C observed for the SS: RBB in both the east-facing living space and the west-facing bedroom.

The temperature fluctuation is higher in the west-facing bedroom over the two-day experiment because of greater glazing exposure from the sliding, folding, double-glazed door facing east toward the patio. The sun's path results in increased exposure to direct sunlight on the glazed door from sunrise until noon. The fluctuation decreases over the next six hours from noon to 6 pm as the sun moves westward, casting shade on the east-facing glazed door of the bedroom. During this period, the fluctuation in the living space is lower due to the west-facing glazed door being exposed from noon until sunset.

- **Indoor Relative Humidity fluctuations in 6-hour interval regarding East-oriented living (Liv.) and West-oriented bedroom (BRm.) on reference days without shading and experimental days with SS: RBB in July 2023**

Fig. 94 and 95 illustrates the fluctuation rate of RH in July 2023, highlighting the differences between experiments conducted on reference days and those on SS: RBB days in the east-oriented living room and west-oriented bedroom. The RH percentages in the living room, when compared, are higher by 7-8% during SS: RBB days compared to reference days, remaining consistent at 60-62%. In the bedroom, the RH percentage ranges from 73-75% on SS: RBB days, while it varies between 66-75% on reference days.

Fig. 95 shows the RH percentage in the bedroom on reference and SS: RBB days, which exhibits minimal variance, attributed to longer occupancy durations for living and working. On day two of the experiment, there is a 7% drop in RH for the living room and bedroom, whereas the external RH percentage shows an increase of 5-7%. (Refer Table 32, Appendix D)

Fig. 94 and 95 demonstrate a consistency in RH percentages in both the living room and bedroom achieved during SS: RBB, with a higher rate of fluctuation observed outdoors on reference days.

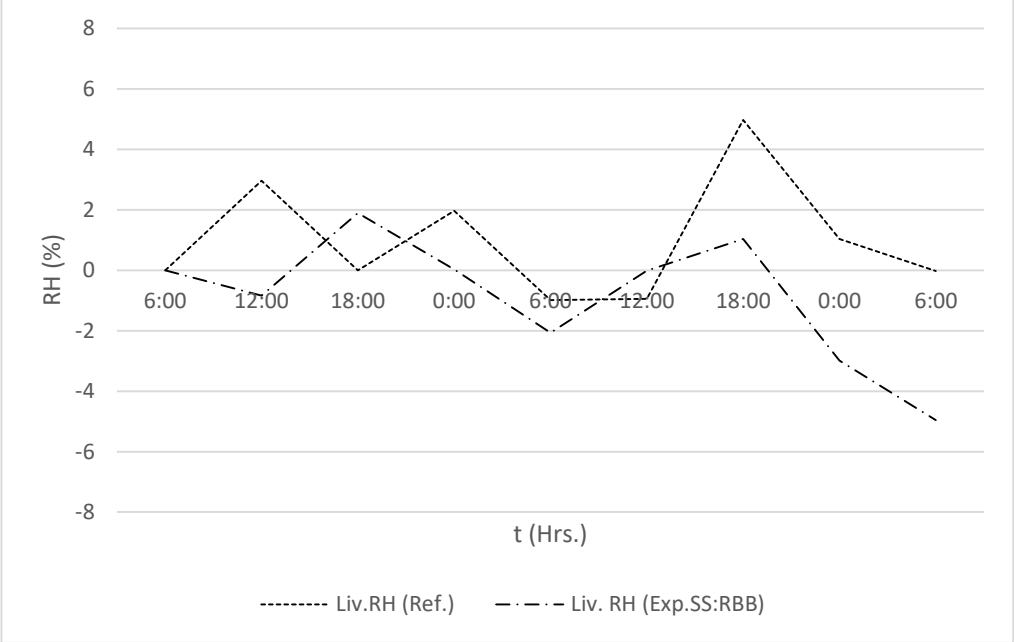


Figure 94: RH fluctuations in 6 hours' intervals at the Liv. (Ref.) & Liv. Exp. SS: RBB in July

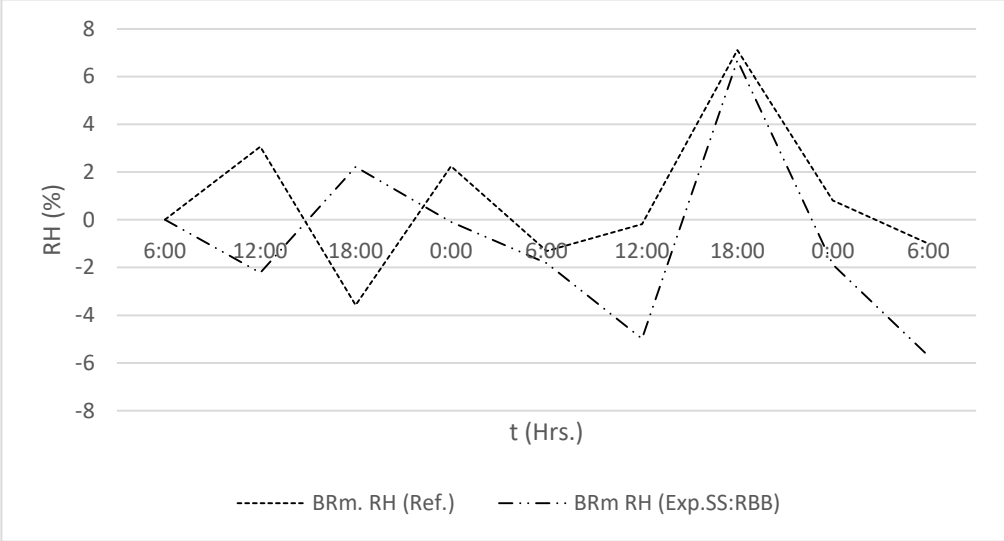


Figure 95: RH fluctuations in 6 hours' intervals at the Liv. (Ref.) & Liv. Exp. SS: RBB in July

- **Indoor air temperature fluctuations in 6-hour interval regarding East-oriented living (Liv.) and West-oriented bedroom (BRm.) on reference days without shading and experimental days with SS: RBB in August 2023**

Fig. 96 and 97 shows reduced temperature fluctuations over 6 hours from 6 am to 12 noon, comparing Reference Day 1 with no solar shading to Experiment SS: RBB for the east-facing living room and west-facing bedroom. On Day 2, Experiment SS: RBB shows an even greater

reduction in temperature fluctuations, maintaining a steady indoor temperature in both the living room and bedroom within 27–30 °C. On Day 1, the bedroom without solar shading experienced a 2°C temperature difference from 6am to 6 pm With solar shading, this difference drops to less than 1°C. On Day 2, temperatures in the living room and bedroom started to decrease with solar shading, while they increased by 2°C in both rooms without shading. The bedroom had a temperature about 1°C higher than the living room when both were shaded, due to its eastern exposure and the sun's path affecting the west-facing room. The shading on the patio, designed architecturally, helps block direct sunlight from impacting the west-facing glazed door of the living room. The solar shading shows potential to lower temperatures by 2°C and helps keep indoor temperatures more stable by reducing fluctuations. (Refer Table 33, Appendix D)

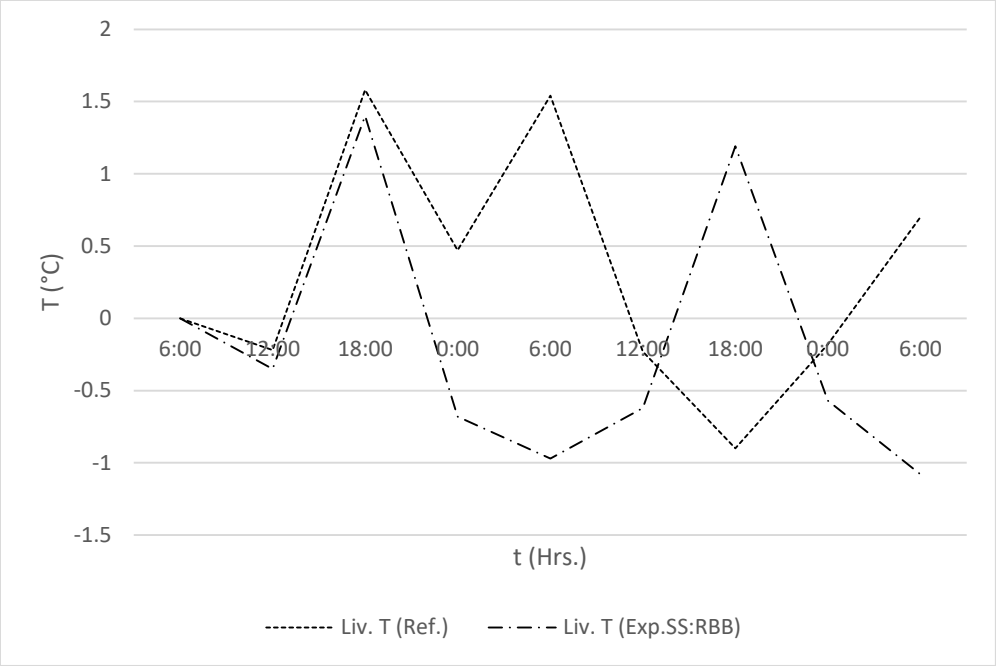


Figure 96: Indoor Air temperature fluctuations in 6-hour interval at the Liv. (Ref.) & Liv. Exp. SS: RBB in August

The Fig. 96 and 97 display similar patterns of temperature fluctuations in the living room and bedroom, maintaining a consistent variation within a 1°C range compared to the reference day's indoor temperature, with no significant differences indicating higher or more variable temperature fluctuations.

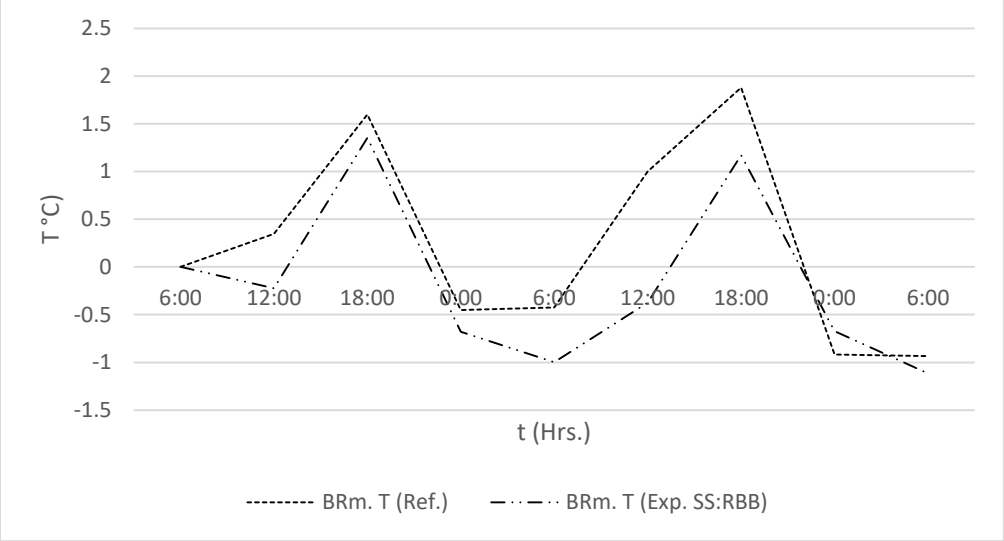


Figure 97: Indoor Air temperature fluctuations in 6-hour interval at the BRm. (Ref.) & BRm. Exp. SS: RBB in August

Indoor Relative Humidity fluctuations in 6-hour interval regarding East-oriented living (Liv.) and West-oriented bedroom (BRm.) on reference days without shading and experimental days with SS: RBB in August 2023

Fig. 98 and 99 shows a low level of RH fluctuation in August for Ref. and Exp. SS days due to the cloudy sky. The RH % demonstrates a more consistent range of 68 to 75% in east-facing living areas and 65 to 73% in west-facing bedrooms with SS. The fluctuation rate decreases with SS compared to Ref. days without SS. (Refer Table 34, Appendix D)

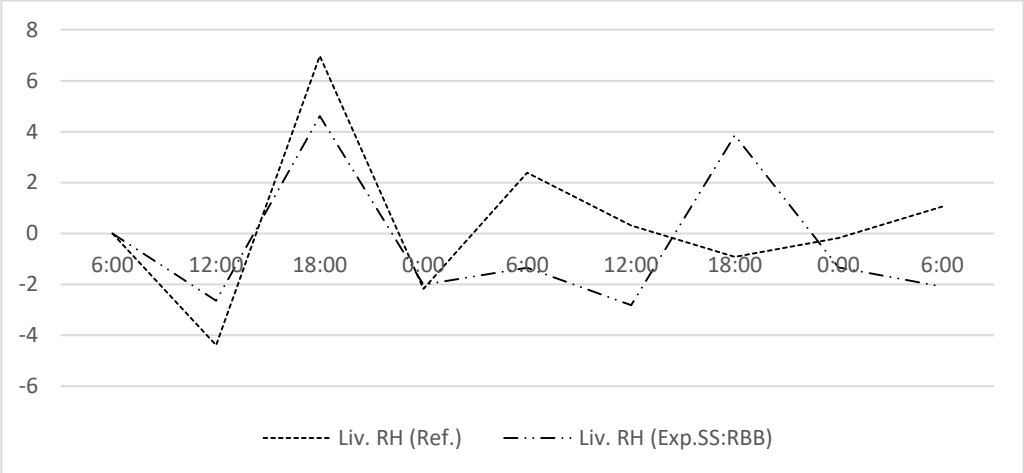


Figure 98: RH fluctuations during a 6-hour gap at the Liv. (Ref.) & Liv. Exp. SS: RBB in August

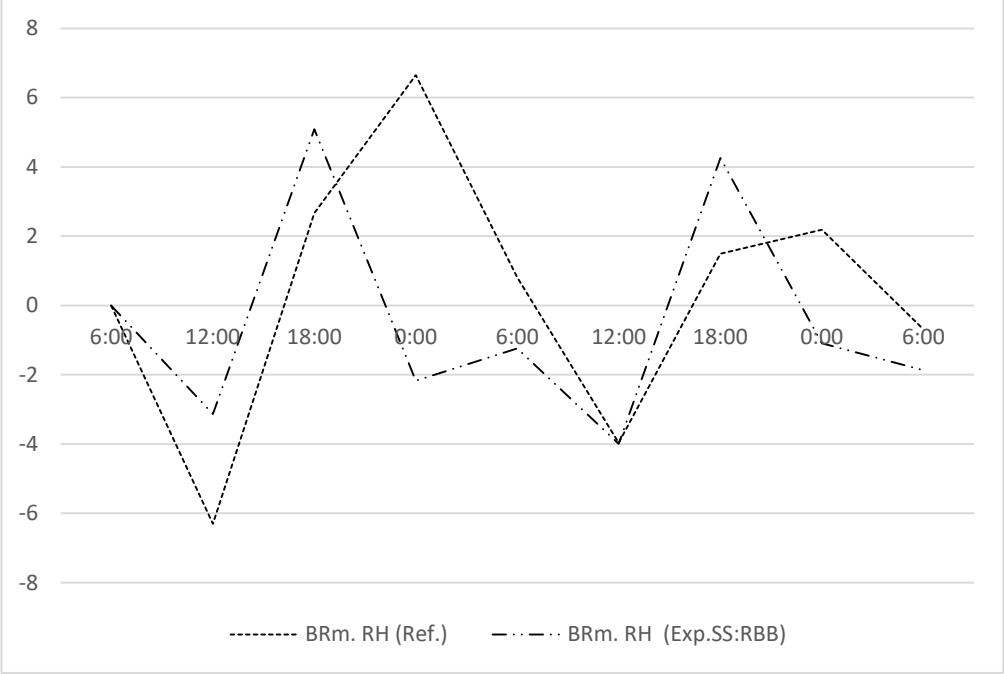


Figure 99: RH fluctuations in 6 hours gap at the BRm. (Ref.) & BRm. Exp. SS: RBB in August

On day 2 of SS: RBB Exp., RH % drops about 5% compared to the same interval in the living and bedroom areas without SS on the Ref. Exp. day 2. Outdoor RH % on Ref. days ranged from 75% at 6 am to 11% at 12 noon. On the Exp. SS day, RH % was 56% at 6 am and remained 6% at 12 noon. A consistent indoor RH % range of 60 to 70% is maintained due to the BK envelope system. SS: RBB helps to further sustain this consistency with a maximum fluctuation rate of 5%. (Refer Table 34, Appendix D)

- **Indoor air temperature fluctuations in 6-hour interval regarding East-oriented living (Liv.) and West-oriented bedroom (BRm.) on reference days without shading and experimental days with SS: RBB in September 2023**

Table 35 (Refer Appendix D) shows a 2°C temperature variation between Reference Day 1, with no solar shading, and Experiment SS: RBB. Throughout the 48-hour experiment, the living room and bedroom with SS: RBB maintain a consistent temperature of 28 to 30 °C, while the outside temperature on Day 2 reaches 49.4°C.

Fig. 100 shows the east-facing living room records temperatures that are 0.5 to 1°C higher than those in the west-facing bedroom as seen in Fig. 101. This difference is due to the large shaded sliding folding glazed door facing west, which receives direct sun rays from 1 pm to sunset; during

this time, the west-facing glazed door benefits from shading provided by the patio's architectural design. (Refer Table 35, Appendix D)

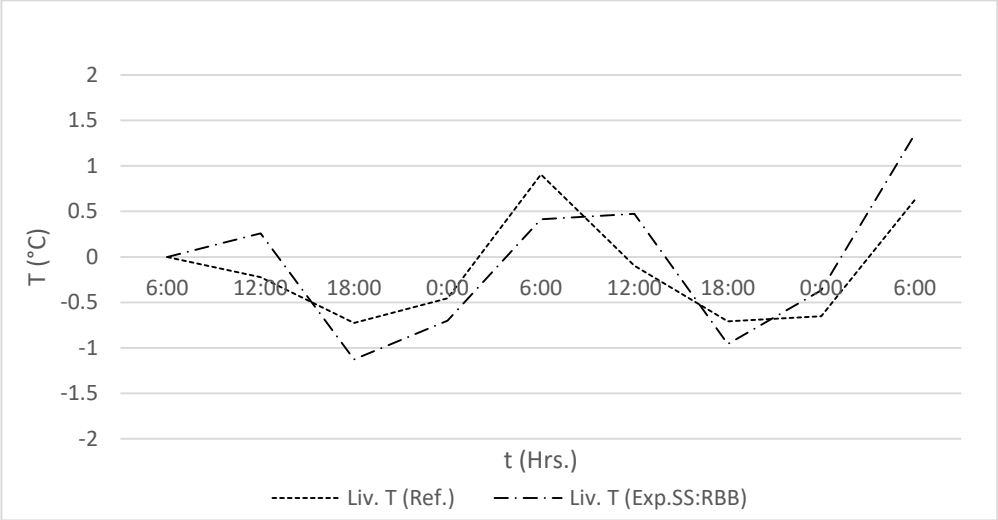


Figure 100: Air temperature fluctuations during a 6-hour gap at the Liv. (Ref.) & Liv. Exp. SS: RBB in September.

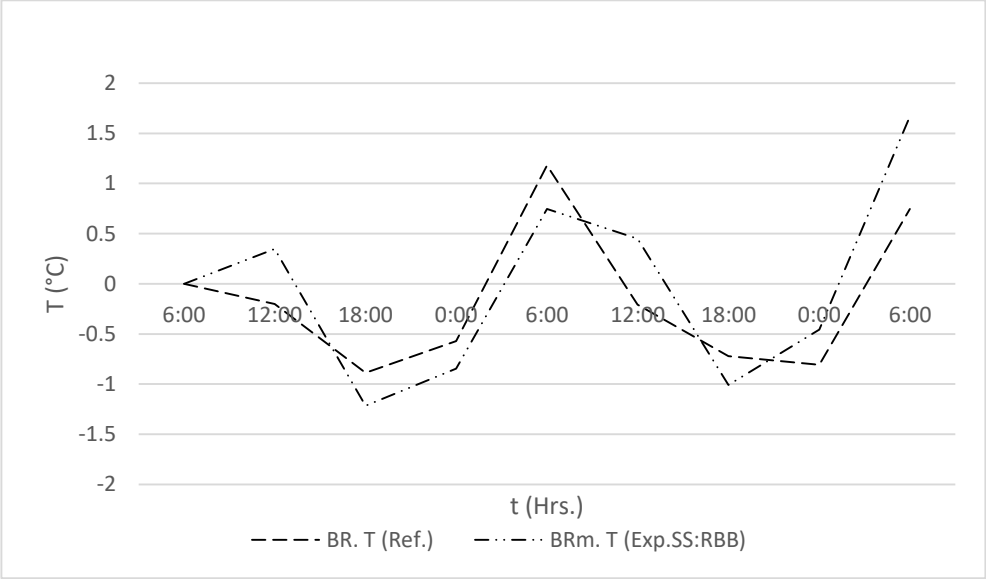


Figure 101: Air temperature fluctuations during a 6-hour gap at the BRm. (Ref.) & BRm. Exp. SS: RBB in September.

The Fig. 100 and 101 show a similar pattern of temperature fluctuations in the living room and bedroom, maintaining consistency within a 1°C range compared to the reference day's indoor temperatures, with no significant stationary periods showing higher and more variable temperature fluctuations.

Table 36, (Refer Appendix D) shows a low level of RH fluctuation in September, with 54 to 57% in the living room, 66 to 72% in the bedroom on the reference day, and 48 to 54% in the living room and 57 to 67% in the bedroom on experimental SS days. The RH% outdoors on the reference day fluctuated between 19 to 70% and 5 to 60% on experimental SS days.

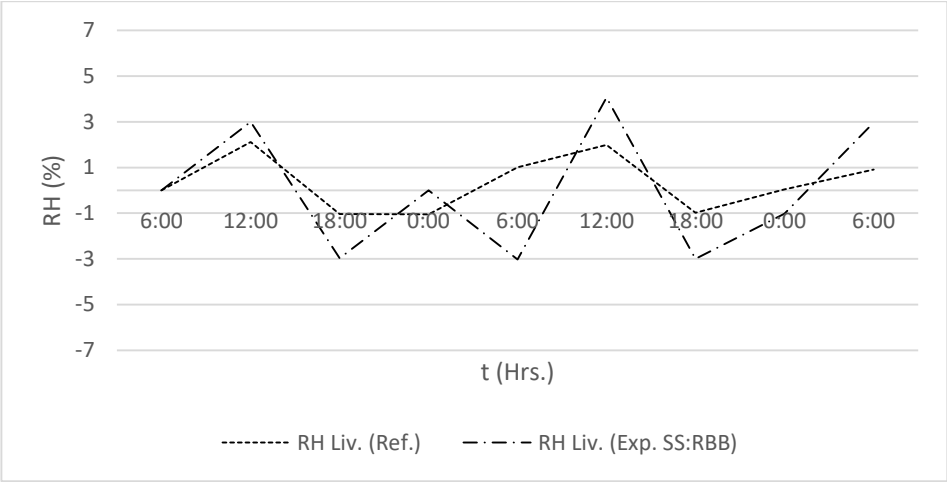


Figure 102: RH fluctuations over a 6-hour gap at Liv. (Ref.) & Liv. Exp. SS: RBB in September

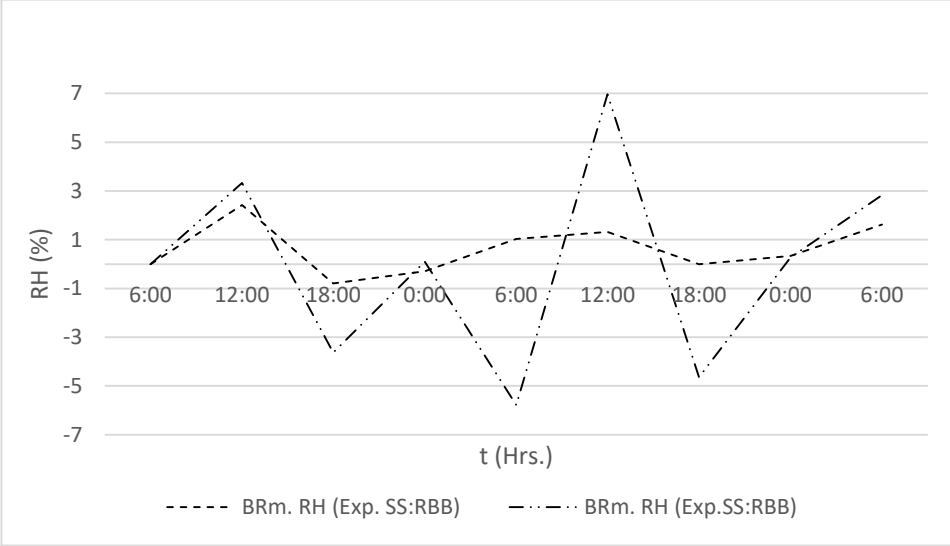


Figure 103: RH fluctuations in 6 hours gap at the BRm. (Ref.) & BRm. Exp. SS: RBB in September

The relative humidity fluctuations as indicated in Fig. 102 and 103, Table 28 presents outdoor temperature, RH, wind speed, and direction. There is high fluctuation in RH% outdoors with rising temperature. The RH% in the west-oriented bedroom is 10-12% higher than in the east-oriented

living room. This is caused by the higher temperature in the living room compared to the Bedroom. (Refer Table 36, Appendix D)

Table 28: Outdoor temperature, relative humidity, wind speed, and wind direction on reference and experimental summer study days in September.

	CONTEXT DATA - At BK site Location - TSC 20 & 21 Sept 2023					CONTEXT DATA - At BK site Location - TSC 23 & 24 Sept 2023				
Parameter	**Outdoor**		**Solar Radiation**	**Wind Speed**	**Wind Direction**	**Outdoor**		**Solar Radiation**	**Wind Speed**	**Wind Direction**
Experiment Time- HR: MIN	Temp. (°C)	Relative Humidity (%)	Watt per square meter	km/h	cardinal direction	Temp. (°C)	Relative Humidity (%)	Watt per square meter	km/h	cardinal direction
6:00	33.7	50	0	0.9	NE	30.6	64	0	0.9	SSE
12:00	44.8	19	824	2.2	WSW	46.6	5	839	1.3	ENE
18:00	39.6	43	30	0.9	WNW	40.2	31	24	1.3	ENE
0:00	34.1	58	0	0	NE	34.4	15	0	0.4	NE
6:00	30.8	64	0	0.4	S	32.1	19	0	0.9	ENE
12:00	44.6	19	858	0.9	SW	45.1	1	871	2.7	SSE
18:00	38.8	52	17	0.4	SW	40	28	22	0.9	ESE
0:00	34.4	68	0	0	NE	34.9	13	0	0.9	ENE
6:00	30.6	70	0	0	ENE	31.8	10	0	0	SE

4.2.1 (v) Summary for Experimental analysis of Solar Shading indoor effects

The benefits in indoor air temperature reduction potentials (°C) during the peak summer months with the action of the dynamic Solar Shading curtain RBB, ETC, and ITC are as indicated in the Table 29.

Table 29: Indoor air temperature reduction potential with action using dynamic Solar Shading Curtain RBB, ETC, ITC

Exp. Month / Season	Dynamic Solar Shading Curtain (SSC)						Reference Table for data analysis
	RBB		ETC		ITC		
	East Oriented Room	West Oriented Room	East Oriented Room	West Oriented Room	East Oriented Room	West Oriented Room	
July	8°C	7°C	4°C	4°C	3°C	3°C	24
August	5°C	5°C	2°C	2°C	1°C	1°C	
September	3°C	3°C	2°C	2°C	1°C	1°C	

The external fixed Solar Shading RBB for windows demonstrates more effectiveness in preventing solar radiation from warming the glass and transferring heat inside.

Between the East- and West-oriented rooms, the impact of indoor air temperature reduction with Action: Solar Shading RBB, ETC & ITC was less than 1°C.

The indoor air temperature ranges at BK living lab with action of SS RBB in comparison to the external temperature is as shown in the Table 30.

Table 30: Indoor air temperature range at BK living lab compared with the exterior temperature range at the BK living lab location.

Exp. Month / Season	Indoor air temperature range achieved with the impact of Action SS: RBB	External Temperature range	Reference Table
July	29°C – 32°C	31°C – 47°C	70
August	27°C – 29°C	30°C – 46°C	71
September	27°C – 30°C	30°C – 45°C	72

The indoor temperature stays between 27-30 °C at noon, even during peak summer when the outside temperature reaches 48 °C, using SS: RBB.

The indoor air temperature fluctuation at a range of 1°C was observed for the action SS: RBB in both the east-facing living space and the west-facing bedroom in July when at exterior with n action a temperature fluctuation 2.5°C with no action (Refer Table 73). The envelope system's

layered composite wall and its thermal inertia help regulate heat delay and temperature drop, maintaining indoor comfort during summer and preventing overheating.

4.2.2 Experimental analysis of Natural Ventilation indoor effects

This session presents an analysis of data collected during the Natural Ventilation experiments, divided into four parts to provide an overall perspective on the impact of bioclimatic actions, as well as the details of individual rooms within the experimental zone.

An overview of temperature reduction potential using natural ventilation measures for the winter and transitional seasons.

The experimental results for natural ventilation during winter and transitional seasons are presented in Table 38. The Eq. 4 used to find the ($\Delta T^{Room}_{air,\ ACTION\ Benefits}$), air Temperature reduction potential with active bioclimatic action of Natural Ventilation for the experiment scenarios as indicated in Table 14, Fig. 71, during the 48-hour experiment. The comparison of indoor air temperature (°C) differences achieved through natural ventilation in the BaityKool lab is shown for January, March, and April 2024. The variation in potential indoor air temperature reduction (°C) between the experimental zones—the east-oriented living room and kitchen, and the west-oriented bedroom — is expressed in terms of minimum (Min.), maximum (Max.), and average (Avg.) values over the duration of the experiments.

Action Natural ventilation experiments conducted at the BK living lab with the actions outlined below (Cf. Section 3.3.2, Figure 69, Table 13):

- Day Ventilation + Night Ventilation (DV+NV),
- Night Ventilation (NV),

Table 31: The indoor air temperature (°C) reduction potentials $\Delta T^{Room}_{air,\ ACTION\ Benefits}$ (cf. Section 3.6.1, Eq. 4) during winter and transitional season, between actions use of Natural Ventilation DV+NV, NV, and No natural ventilation.

	Exp. DV + NV JAN 24		Exp. NV Set 1 Jan 24		Exp. NV Set 2 April 24	
	East	West	East	West	East	West
Natural Ventilation	**Liv.**	**BRm.**	**Liv.**	**BRm.**	**Liv.**	**BRm.**
Min	1	1	1	1	1	1
Max	3	5	5	5	2	3
Average	2	3	3	3	1	2

Comparison of the indoor air temperature difference (°C) achieved in the East- and West-oriented rooms of the BaityKool living lab experimental zone through experiments on natural ventilation during January and the transitional months of March and April 2024.

Exp. DV + NV

The Table 40 shows the temperature reduction potential during the winter season in January 2024 under passive conditions, with an average of 2-3°C achieved when the external temperature ranged from 16°C at 6 am to 32°C at 12 noon. A greater temperature benefit was observed in the west-facing bedroom, as shown in Table 38, due to the winds from the SW throughout the experiment, which improved the exchange of cooler outdoor air indoors through wind drafts.

Exp. NV

The experiment was conducted in January 2024, during the winter season, and in April, the transition season. Table 40 shows the results for T reduction potential in January, with an average of 3°C achieved while the external T ranged from 16°C at 6 am to 32°C at noon. The T reduction potential during the transitional season in April had an average of 1°C.

4.2.2 (i) Potential temperature reduction using Natural Ventilation (Nat.V) action: Day Ventilation & Night Ventilation (DV + NV) during 48-hour experiment

The details of the potential indoor air temperature (°C) reduction due to Natural Ventilation during the 48-hour experiment are presented in Table 32. Temperature difference data (°C) were recorded at 1-hour intervals over the entire 48-hour period. The Eq.2 used to find the temperature difference achieved with the experiment ($\Delta T_{air,\mathrm{EXP}}^{Room}$), Eq. 3 to find the indoor air temperature °C difference with No Action at Experiment as baseline reference ($\Delta T_{air,\mathrm{REF}}^{Room}$). The difference between the $\left(\Delta T_{air,\mathrm{EXP}}^{Room}\right)$ and ($\Delta T_{air,\mathrm{REF}}^{Room}$) enables the assessment of air temperature reduction potential with active bioclimatic action Natural Ventilation using Eq.4. The benefits of natural ventilation and the indoor temperature reduction achieved for Minimum (Min.), Maximum (Max.), and average (Avg.) temperatures are provided for days 1 and 2.

The January temperatures range from 16 to 32 °C, offering the opportunity to use cooler outdoor air for indoor comfort through natural ventilation. The experiment was conducted over a two-day

(48-hour) reference period without ventilation, followed by two days (48 hours) incorporating Day and Night Ventilation (DV+NV). An analysis compared the temperature differences between the reference and experimental days, focusing on the cooling potential for east- and west-oriented rooms. The experiment was carried out under passive conditions, using natural ventilation inside BK lab during the day and night. The temperature reductions in east- and west-facing rooms during the DV+NV period are shown in Table 32.

The potential temperature benefit in January can reach up to 3 °C, with external temperatures ranging from 16 to 34 °C. A greater benefit is possible when external temperatures are between 13 and 24 °C. Table 31 shows the lowered outdoor temperatures from 9 pm to 6 am. The temperature difference achieved with the action DV+NV is shown in Table 32.

Table 32: The indoor air temperature (°C) reduction potentials $\Delta T^{Room}_{air,\ ACTION\ Benefits}$ *(cf. Section 3.6.1, Eq. 3) during winter and transitional season with action DV+NV in East-oriented Living. & West-oriented Bed Room.*

Natural Ventilation: Day & Night Ventilation: **Exp. DV + NV - JAN 24**		
Orientation	East	West
t	**Liv.**	**BRm.**
6:00	-3	-5
12:00	2	2
18:00	4	4
0:00	-2	-3
6:00	-2	-2
Max	**-3**	**-5**
Min	**0**	**0**
Average	**0**	**-1**
12:00	1	1
18:00	2	2
0:00	1	3
6:00	3	4
Max	**-2**	**-2**
Min	**2**	**2**
Average	**1**	**1**

Note: **(-Ve)** indicated the potential indoor air temperature °C reduction, **(+Ve)** indicated the potential indoor air temperature °C increase

The external Temperature, Relative Humidity, Wind Speed, and Wind Direction at the BaityKool Lab site context are as indicated in Table 42. This presents the external weather conditions for baseline reference (REF) and experiment (EXP) day and night ventilation (DV+NV) days, with 1-

hour intervals, in January for 24 hours. Temperature benefits of up to 2°C at night from 12 am to 6 am as observed in Table 43, (Refer Appendix E). Less temperature reduction indoors is achieved during the day through natural ventilation, as the exterior temperature ranged from 28-32°C between 12 pm and 6 pm.

The Fig.104 and 105 shows the comparison in indoor air temperature (°C) in Living, reference (REF) with external and Patio air temperature on reference and experiment days. The NV can potentially use free cooling when the outside temperature drops below 23°C. Results showed greater effectiveness with a larger reduction in T during January, ranging from 12 to 20°C. Both DV and NV indicate a greater benefit in the west-facing bedroom compared to the east-facing one, due to the wind, as the draft mainly comes from the WSW and SW during both day and night. Indoor temperature at BK living ab remains steady, between 23 and 25°C, even when outdoor temperatures fluctuate from 18 to 30°C. A 2°C drop in indoor temperature occurs at night from 12 am to 6 am when outdoor temperatures fall below daytime levels.

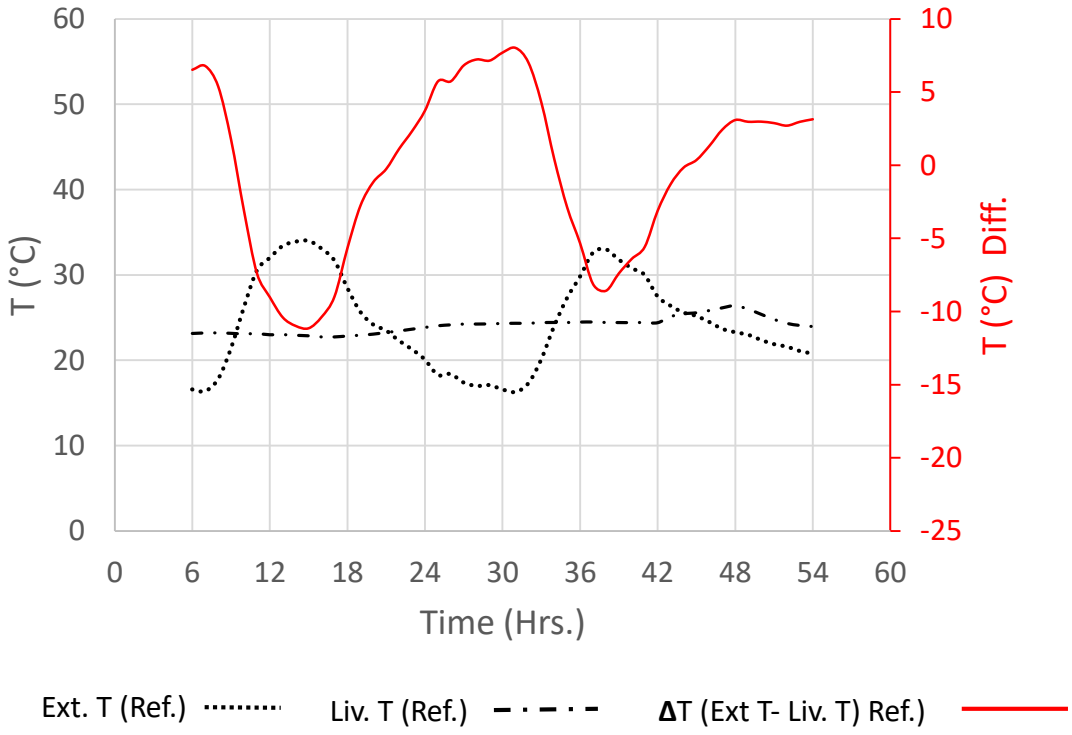


Figure 104: Comparison of indoor air temperature (°C) in Living (Liv.) reference (REF) with external air temperature on REF. day, T Difference between Ext. & Liv. (Ref)

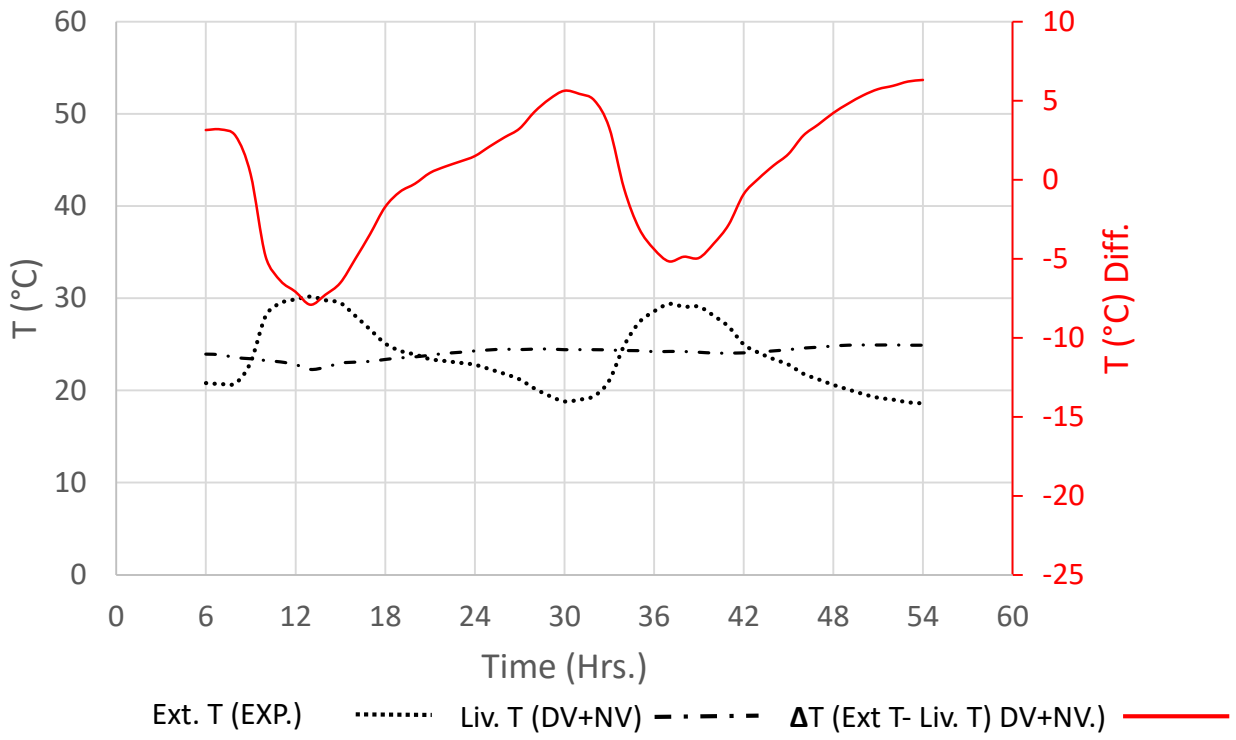


Figure 105: Comparison of indoor air temperature (°C) Liv. with external air temperature on EXP. DV+NV day, T Difference between Ext. & Liv. (DV + NV)

- **Indoor air temperature fluctuations at 3-hour intervals at Liv. & BRm. during EXP. DV+NV days**

The indoor air temperature fluctuation at 3-hour intervals between reference (REF) and experiment (EXP), Natural ventilation, Day ventilation, and Night ventilation (DV+NV) are presented in Fig. 106 and 107 (Refer Table 81 for January 2024, Appendix E)

A comparison of East-oriented and West-oriented living is analyzed in the context of the prevailing wind direction at the BaityKool lab site.

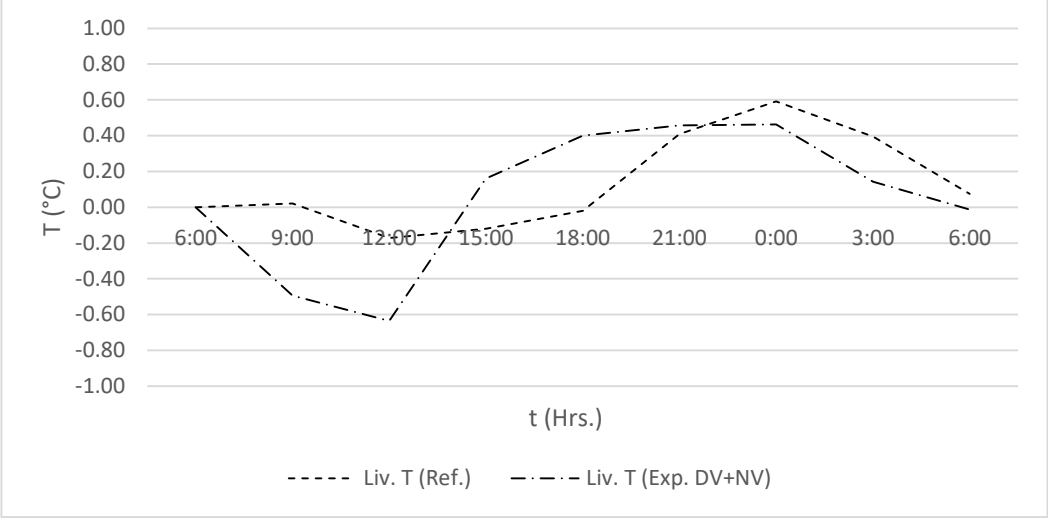


Figure 106: Indoor air temperature fluctuations at 3-hour intervals at the Liv. (Ref.) & Liv. Exp. DV+NV in January

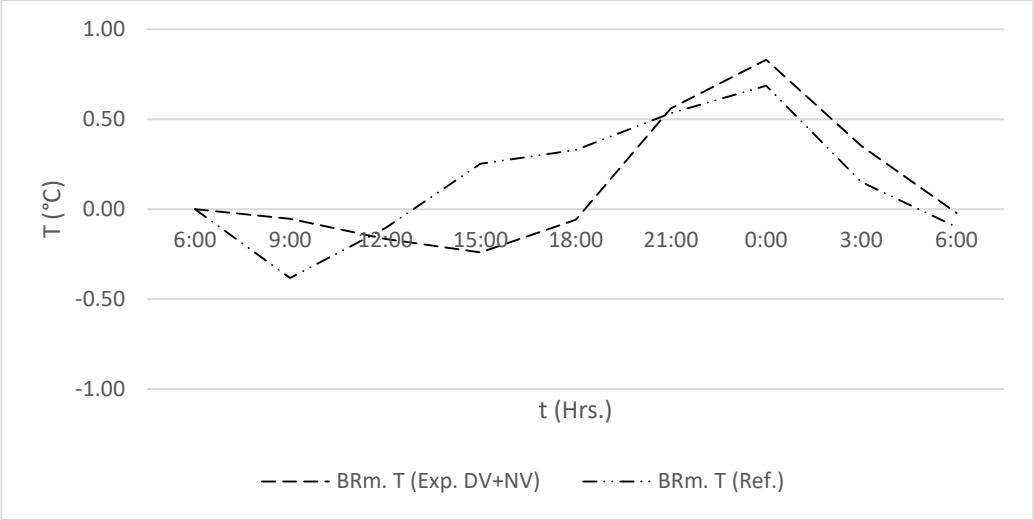


Figure 107: Indoor air temperature fluctuations in 3-hour intervals at the BRm. (Ref.) & BRm. Exp. DV+NV in January

The indoor air temperature fluctuation as in figure 106 and 107 shows a temperature drop indoors at Liv. & Brm from 6am to 12 pm, achieved through cross ventilation that allows the cooler outside air to lower the indoor air temperature. The envelope system helps maintain a consistent air temperature at indoors observed with a fluctuation range of only 0.5°C. The thermal inertia of the interior wall and floor contributes to maintaining a consistent indoor temperature. Refer Table 44 , Appendix E)

Action benefits with DV at the indoor of BK living lab

The temperature in the bedroom is lower than in the living room between 6 am and 6 pm. The temperature drops by 0.69 °C in 6 hours, with direct sunlight. In the bedroom, the temperature decreases by 0.1 °C over the same period. This is due to the larger glazing facing east, which is exposed to more solar rays from 6 am to 12 pm.

The indoor air temperature in the living room drops more than in the bedroom. due to the porous UHPC protecting the window glazing from the UV rays.

Fig. 108 demonstrates that wind direction & speed contribute to the rate of indoor air temperature change, resulting in a drop or an increase based on the external (EXT.) temperature. Figure 108 shows BaityKool living lab with the wind direction simulated for January. The exterior air temperature is 20°C on Exp. DV+NV day in Jan. 2024, this rise by 10°C in 6 hrs. But the indoor air temperature drops in 6 hours (Refer Table 43). This is due to the Thermal Inertia of the envelope system releasing the cool energy inwards, letting the indoor air temperature drop faster in Liv. and rise in the BRm. 3 hours earlier than Liv from 6pm onwards due to the predominant winds from WSW from 12pm to 3am.

The higher outside temperature of 30°C on the experimental day did not cause a corresponding increase in internal temperature because the window opening size was smaller. A higher outdoor temperature, combined with strong airflow, can also help maintain thermal comfort for individuals by promoting evaporative cooling through the skin, as airflow facilitates heat transfer between the body and the environment via convection. The window opening size influences this effect to ensure users remain comfortable with their thermal environment.

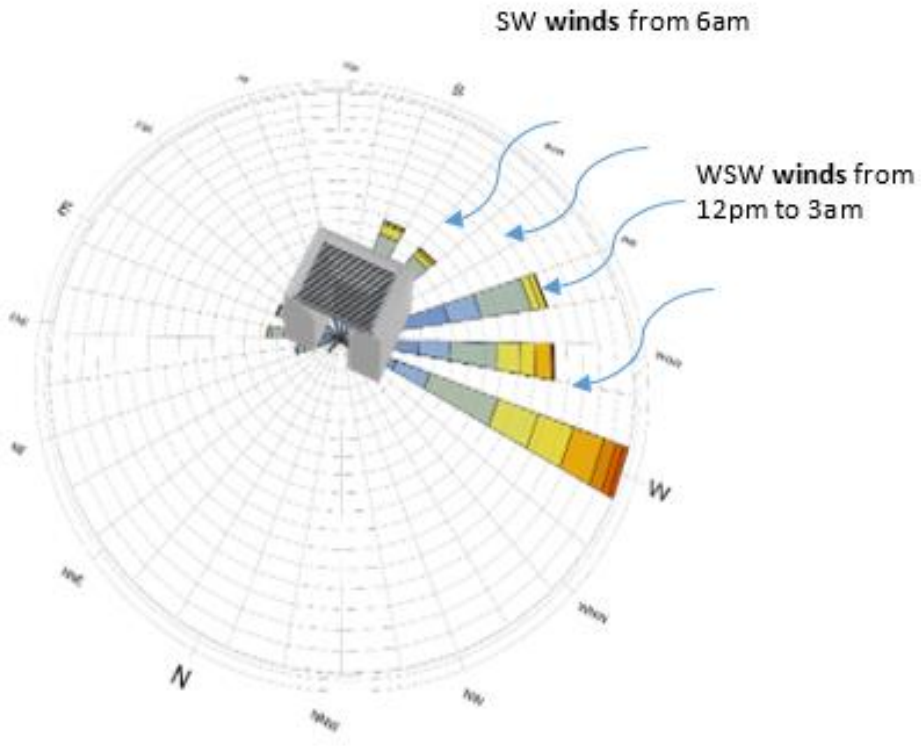


Figure 108: BaityKool view with wind directions in January 2024

Action benefits with NV at indoor of BK living lab

When the outdoor temperature drops by 4°C from 9pm to 6am, the indoor temperature rises by 0.5°C over 3 hours from 9pm to 12am, then falls by 0.5°C over 6 hours from 12am to 6am. Indoor temperatures at night increase due to the thermal inertia of the envelope insulation system.

RH % in BR. At 74%, it drops at night with NV. Compared to DV+NV, the RH% decreases to 60% because of cross ventilation.

4.2.2 (ii) Potential temperature reduction with Natural Ventilation (Nat.V) action: Night Ventilation (NV) during 48 hours of experiment

The data analysis for the Natural Ventilation action, specifically Night Ventilation performance in January and April 2024, shows an overall reduction in indoor air temperature (°C) when using Natural Night Ventilation for the experiment scenario in Section 3.3.2, as illustrated in Fig. 71 and Table 14. This includes temperature differences in the East- and West-oriented rooms of the experimental zone, with and without night ventilation, compared to external temperatures. Tables 48 and 49 present indoor temperatures (°C) and relative humidity (%) for the east- and west-oriented rooms, along with external temperature, relative humidity, wind direction, and wind speed

during the baseline reference days and the night ventilation action. The Eq. 2 used to find the air temperature difference ($\Delta T_{air,\mathrm{EXP}}^{Room}$) with the action Night ventilation. Eq. 3 used to find the indoor air temperature °C difference with No Action at Experiment as baseline reference ($\Delta T_{air,\mathrm{REF}}^{Room}$). The Eq.4 used to find the difference between the experiment (EXP) with action and no action (REF). The fluctuations in indoor air temperature, relative humidity, and CO2 over 3-hour intervals are analyzed by comparing scenarios with and without night ventilation.

Table 33 shows experiments were conducted in January and April using a Reference (Ref.) as a neutral scenario, with no cross ventilation. The house's external-facing doors and windows were kept closed, while the internal doors of the kitchen and bedroom remained open. The reference setup was maintained for three days prior to each experiment, with no night ventilation. The night ventilation experiment lasted 24 hours, with windows in the living room, kitchen, bedroom, and patio ventilator opened at 10 pm and closed at 7 am. The external-facing windows and doors had no curtains or roller blinds for solar shading. During the night ventilation (NV) days, the patio-facing door was kept closed, and doors were opened only at the beginning and end of the experiment for setup. (Cf. Section 3.3.2 Experiment & Experimental Scenario: Natural Ventilation (Nat.V.) , Table 3.4)

Table 33:. The indoor air temperature (°C) reduction potentials $\Delta T_{air,\ ACTION\ Benefits}^{Room}$ (cf. Section 3.6.1, Eq. 3) during winter and transitional season with action Night Ventilation (NV) in January and April for the East-oriented Living, Kitchen. & West-oriented Bed Room.

Action	Natural Ventilation: Night Ventilation	Exp. NV Set 1 Jan 24			Exp. NV Set 2 April 24		
		East		West	East		West
		Liv.	Kit	BRm	Liv.	Kit	BRm
Experiment duration 12 hours	18:00	**-3**	-3	**-3**	**-2**	-2	**-3**
	0:00	**-1**	-1	**-1**	**-1**	-1	**-1**
	6:00	**-1**	-1	**-1**	**1**	1	**1**
	12:00	**-5**	-5	**-5**	**0**	0	**0**
	18:00	**-5**	-5	**-5**	**-1**	-1	**-1**
	Max	-5	-5	-5	-2	-2	-3
	Min	-1	-1	-1	1	1	1
	Average	-2	-2	-2	-1	-1	-1

Note: **(-Ve)** indicated the potential indoor air temperature °C reduction, **(+Ve)** indicated the potential indoor air temperature °C increase

Table 46 (Refer Appendix E) shows external temperatures ranging from 16 to 32 °C in January; there was a potential temperature drop of up to 5 °C. In April, the external temperature ranged from 20-34 °C; therefore, the benefit of NV appears to be minimal after 24 hours. The decrease in external temperature from 24 to 20 °C between 12am and 6am did not significantly affect the temperature drop at night with NV.

Fig.109 shows the temperature on the reference day without natural ventilation rises by 1°C over 12 hours from 6pm to 12am, then decreases by 0.7°C over the following 12 hours from 6am to 6pm. It remains steady at 23°C between 12 am and 6pm.

An increase in the Indoor air temperature in Liv. on the NV day, by 2.3 °C from 6 pm to 6 am, followed by a decrease of 2.1 °C over the next 12 hours from 6 am to 6 pm as seen in Fig.109. The air temperature reduction on Ref. day was 0.7 °C in 6 hours. T rises at night for 12 hours with night ventilation. It then decreases during the day, over 12 hours from 6 am to 6 pm, when the living space has no cross ventilation. Comparing the T difference between Ref. and NV days, a benefit of 1 °C is observed in 6 hours and 5 °C over 12 hours during the day from 6am to 6 pm. (Refer Table 47, Appendix E)

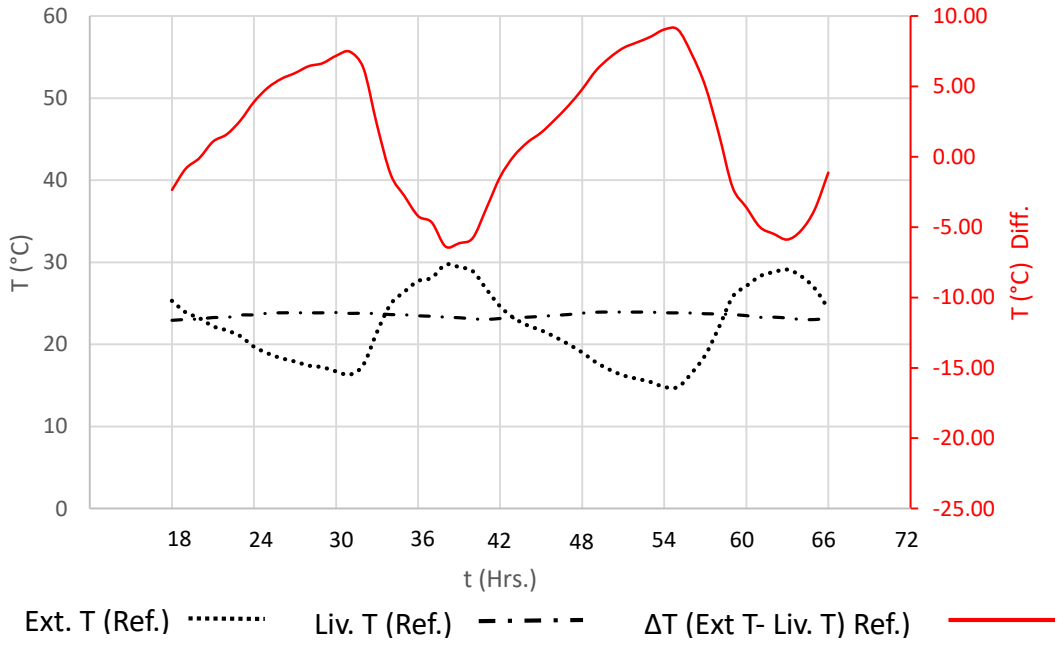


Figure 109: Comparison of indoor air temperature (°C) in Living (Liv.) with external and Patio (Pat.) air temperature on Ref. day

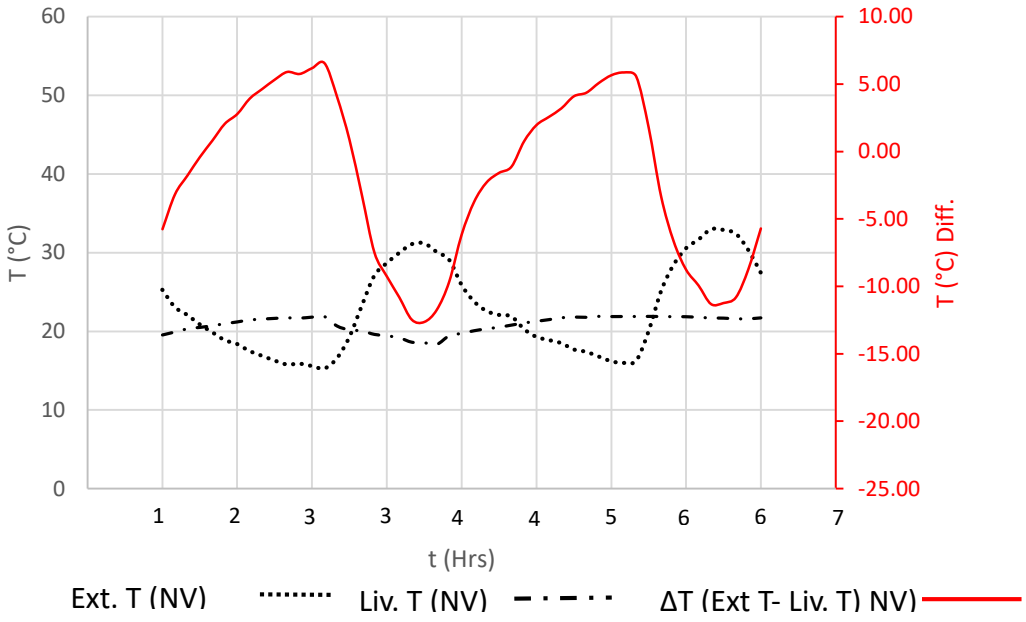


Figure 110: Comparison of indoor air temperature (°C) in Living (Liv.) with external and Patio (Pat.) air temperature on Exp. NV day

Figures 109 and 110 show the comparison between the reference and the night ventilation experiment. The temperature increase with NV is caused by thermal inertia releasing heat stored during the day in the roof and wall insulation at night. The cooler air from the environment gets stored in the clay tile lining of the wall insulation and concrete floor, then releases it during the day, leading to a 5 °C reduction in temperature compared to the reference day.

Table 34 shows that the Temperature and Relative Humidity are consistent in east and west-oriented rooms on the reference day with no night ventilation. The temperature is at 23°C, and relative humidity (RH) is 51-52% in the east-oriented living room and kitchen, while RH is 60-61% in the bedroom. The west-oriented bedroom shows about 10% higher RH than the east-oriented living room and kitchen.

Table 35 shows that Temperature and relative humidity are consistent in both East- and West-oriented rooms during the experience of night ventilation. The temperature drops at 6 am did not affect the indoor temperatures in the living room, kitchen, and bedroom, which ranged from 19 to 22 °C, with relative humidity between 47% and 57% in the east-oriented living room and kitchen, and 54% to 68% in the bedroom. The west-oriented bedroom has about 10% higher relative humidity than the east-oriented living room and kitchen.

Table 34: Comparison in External context T(°C), RH(%), Wind Speed, Wind Direction in 3 hour interval with baseline Reference T(°C) & RH(%) for the east-oriented Living, Kitchen & West-Oriented Bedroom for Exp. NV

		External Context			EAST				WEST	
Time (t) Hrs.	**Ref. Con. T(°C) , 10 Jan 24**	**RH (%)**	**Wind Speed**	**Wind Dir.**	**Ref. Liv. T(°C) , 10 Jan 24**	**Ref. RH Liv. (%) 10 Jan 24**	**Ref. Kit. T(°C) , 10 Jan 24**	**Ref. RH Kit. (%) 10 Jan 24**	**Ref. BRm. T(°C) , 10 Jan 24**	**Ref. RH BRm (%) 10 Jan 24**
18:00	25.3	39	0	SSW	22.9	51	22.8	51	22.9	60
21:00	22.2	51	0	SW	23.2	51	23.1	51	23.3	60
0:00	19.7	58	0	---	23.6	52	23.5	52	23.9	60
3:00	17.9	64	0.4	ESE	23.8	52	23.7	52	24.0	61
6:00	16.7	67	0	---	23.8	52	23.7	52	23.9	61
9:00	21.5	56	0.4	ESE	23.7	52	23.7	52	23.8	61
12:00	27.7	32	0.4	N	23.4	52	23.4	52	23.5	61
15:00	29.4	35	1.3	WSW	23.2	51	23.1	52	23.2	60
18:00	24.6	48	0.4	SW	23.1	51	23.1	51	23.1	60

Table 35: Comparison in External context temperature (°C), RH(%), Wind Speed, Wind Direction in 3 hour interval with Experiment Night Ventilation, T(°C) & RH(%) for the east-oriented Living, Kitchen & West-Oriented Bedroom for Exp. NV

		External Context			EAST				WEST	
Time (t) Hrs.	**Ext. Con. T(°C) 13 Jan 24**	**Relative Humidity (%)**	**Wind Speed**	**Wind Direction**	**Exp. NV Liv. T(°C) , 13 Jan 24**	**Exp.NV RH Liv. (%) 13 Jan 24**	**Exp. NV Kit. T(°C) , 13 Jan 24**	**Exp.NV RH Kit. (%) 13 Jan 24**	**Exp. NV BRm. T(°C) , 13 Jan 24**	**Exp.NV RH BRm. (%) 13 Jan 24**
18:00	25.3	28	0	WSW	19.5	47	19.3	47	19.7	56
21:00	20.9	45	0	---	20.4	47	20.2	47	20.7	54
0:00	18.4	48	0	---	21.1	47	21.0	47	21.6	54
3:00	16.3	51	0	---	21.6	47	21.5	48	21.9	55
6:00	15.6	56	0	---	21.7	48	21.6	48	21.9	56
9:00	19.3	43	0.4	ESE	20.1	50	20.0	51	20.8	57
12:00	28.7	18	1.3	SW	19.4	55	19.1	56	19.9	65
15:00	31.2	15	0.4	WSW	18.5	57	18.2	58	19.0	68
18:00	25.9	23	0	---	19.7	53	19.6	53	19.8	63

- **Indoor air temperature fluctuations on Ref. & Exp. NV days at Liv. Oriented East in January 2024**

The indoor air temperature fluctuation at 3-hour intervals between reference (REF) and experiment (EXP), Natural Night ventilation (NV), is presented in Table 50 for January 2024. A comparison between the reference experiment with no action and with action between the East-oriented Living and the West-oriented Bedroom.

The Table 50 (Refer Appendix E) shows the indoor air temperature fluctuation with the graph in Fig. 111 and 112 shows a temperature drop indoors observed after 12 hours at Liv. & Brm from 6am to 12 pm, achieved through cross ventilation at night that allows the cooler outside air to lower the indoor air temperature. The envelope system helps maintain a consistent air temperature at indoors observed with a fluctuation range of only 0.5°C. A higher air temperature drop is seen in the West-oriented bedroom between 12 pm to 6.00 pm during the non-ventilated hours due to the thermal inertia of the interior wall and floor contributes to maintaining a consistent indoor temperature. This is due to the prevailing winds in the WSW able to capture a wind draft from the West to the East with the activated cross ventilation.

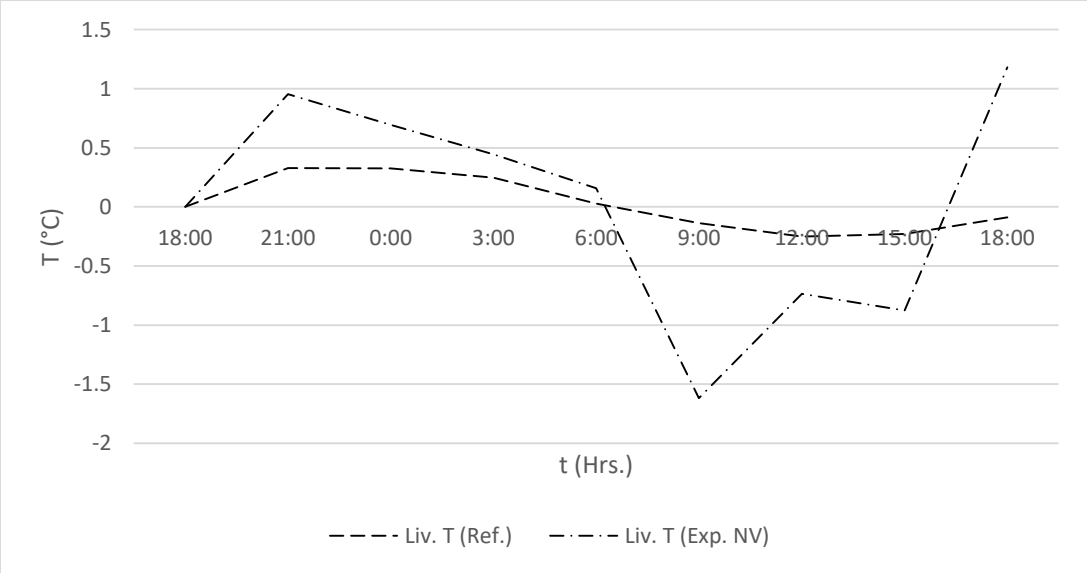


Figure 111: Indoor air temperature fluctuations in 3 3-hour interval at the Liv. (Ref.) & Liv. Exp. NV in January

The impact of action night ventilation can be observed from 9.00 to 18.00 hours with a reduction in air temperature 1°C to 1.5°C happening after 12 hours of the action as seen in Table 50. The

Fig.111 shows living when compared with West-oriented bedroom as in Fig. 112 with a fluctuation in air temperature at 12 noon on day 2 on the East- oriented living caused due to the higher exposure of this space to the solar heat gain in comparison to the West-oriented room.

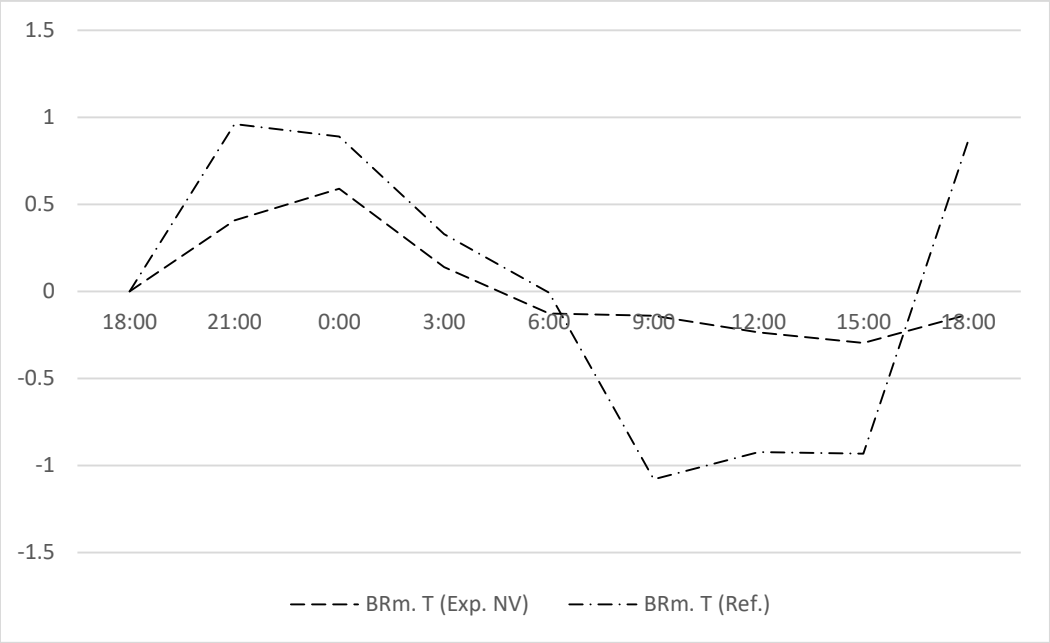


Figure 112: Indoor air temperature fluctuations in 3-hour intervals at the Liv. (Ref.) & Liv. Exp. NV in January

- **Fluctuation in Relative Humidity (%) with action Night Ventilation in East-Oriented Living. & West-Oriented Bedroom. in January 2024**

Table 51 shows the indoor Relative Humidity fluctuation, which shows the RH at the exterior has a range of fluctuation as 39% to 67%, and the indoor has a consistent RH % with the drop observed during the hours of night ventilation.

The RH as indicated in Table 36 in the Living area on the Reference day remains steady at 50-52%, while the contextual RH on the same day shows variations. On the Experimental NV day, the RH at 6pm was 28%, rising to 56% by 6am within 12 hours, then dropping to 18% in the next 6 hours and increasing by 5% in the following 6 hours. Nighttime cross ventilation had no impact on indoor RH in the Living area. The RH stayed within the comfortable range of 50% according to ASHRAE standards.

Table 36: Comparison between Ext. RH (%) with base line reference ($\Delta RH^{Room}_{air,REF}$) & Experiment ($\Delta RH^{Room}_{air,EXP}$) for East-Oriented Living & West- Oriented Bedroom at 3 hour interval in January (cf. section 3.6.1, Eq 6 & Eq.7)

Time (t) Hrs.	Ext. RH (%)	Ref. RH Liv. (%) 10 Jan 24	Exp.NV RH Liv. (%) 13 Jan 24	Ref. RH BRm (%) 10 Jan 24	Exp.NV RH BRm. (%) 13 Jan 24	
18:00	39	51	47	60	56	Night
21:00	51	51	47	60	54	
0:00	58	52	47	60	54	
3:00	64	52	47	61	55	
6:00	67	52	48	61	56	Day
9:00	56	52	50	61	57	
12:00	32	52	55	61	65	
15:00	35	51	57	60	68	
18:00	48	51	53	60	63	
Action		No NV	NV	No NV	NV	

Co2 fluctuation in Liv. & BRm with Night Ventilation in January 2024.

The Table 37 shows the Co2 fluctuation in 3-hour intervals with the effect of natural ventilation on East facing Liv. & West facing BRm.

Table 37: Co2 fluctuation in 3-hour intervals showing the effect of natural ventilation on East facing Liv. & West facing BRm.

Time (t) Hrs.	Ref. CO2 Liv. 10/01/24	Diff. RH % in 3 Hrs.	Exp. . CO2 Liv. 13/01/24	Diff. RH % in 3 Hrs.	Ref. CO2 BRm. 10/01/24	Diff. RH % in 3 Hrs.	Exp. . CO2 BRm. 13/01/24	Diff. RH % in 3 Hrs.
18:00	429	0	445	0	435	0	426	0
21:00	419	-10	429	-16	428	-7	410	-16
0:00	416	-2	416	-12	428	0	423	13
3:00	416	0	418	2	430	2	421	-2
6:00	420	4	425	6	435	5	427	6
9:00	435	15	441	16	446	11	445	18
12:00	432	-3	422	-19	444	-2	439	-6
15:00	422	-9	418	-4	438	-6	435	-4
18:00	430	8	486	69	442	4	507	72

RH% on the reference day in the bedroom was consistently at 60%. During hours of cross ventilation, the Exp. NV showed a steady RH% of 54-56%, increasing by 9% over six hours from

6am to 12pm Additionally, the bedroom temperature dropped by 1°C. There was no significant effect of NV on RH fluctuations in the bedroom, compared to the context RH%, which showed high variation.

4.2.2 (iii) Summary for Experimental analysis of Natural Ventilation indoor effects

DV+ NV benefits

Potential free cooling is achieved with DV and NV when the outside temperature drops below 23°C. A consistent indoor air temperature 23°C – 24°C was observed during the Action DV + NV when the external air temperature is at a range of 16°C -32°C.

The indoor air temperature drops by 1°C - 2°C in the East-oriented Liv. and the West-oriented Brm. from 6:00 to 18:00 hours, with cross ventilation during the day when the external temperature rises by 10°C. A 2°C rise in indoor temperature was observed at night from 0.00 to 6.00 hours with NV when outdoor temperatures fell below daytime levels (Refer Table 39).

The indoor air temperature fluctuations are limited to only 0.5°C, maintained due to the thermal inertia of the interior wall and floor. The envelope system helps maintain a steady indoor temperature.

Wind direction & speed add to the rate of indoor air temperature change with drop or increase based on the external (EXT.) temperature.

NV Benefits

There is a potential indoor air temperature drop of up to 5 °C when external temperatures range from 16 to 32 °C in January.

There was minimal indoor air temperature reduction potential in April with the exterior temperature rising at a range 20 to 34°C.

The NV lets the indoor air temperature show a gradual reduction potential of 1°C in 12 hours between 18.00 and 6.00 hours with cross ventilation, followed by a drop of up to 5°C in the next 12 hours during the day with no cross ventilation.

Comparing the experiment with the action of NV and the reference with no action reveals that the temperature increase with NV is caused by thermal inertia releasing heat stored during the day.

The cooler air temperature from the environment gets stored in the clay tile lining of the wall insulation and concrete floor, then released during the day, leading to a 5 °C reduction.

4.2.3 Experimental analysis of natural Night Ventilation and Solar Shading indoor effects

This session presents an analysis of data collected during the combined strategy of Natural Ventilation and Solar Shading as an experiment to understand the impact of bioclimatic actions during the transitional season with Night Ventilation taking advantage of the diurnal temperature range for free cooling of indoors and the Solar Shading reduce the solar heat gain prolonging the thermal comfort achieved with free cooling of individual rooms in the experimental zone.

Potential temperature reduction using actions: Night Ventilation and Solar Shading (NV+SS) during 48-hour experiment

The overall indoor air temperature reduction (°C) achieved through Natural Night Ventilation with Solar Shading RBB & ETC, as tested in March and April, is presented in Table 53. This data aligns with the experiment scenario described in Section 3.3.3 and is illustrated in Figure 74 and Table 16. It includes temperature differences in the East- and West-oriented rooms of the experimental zone, both with and without night ventilation and solar shading, compared to external temperatures. Table 54 details the indoor air temperature (°C) difference between the east- and west-oriented rooms by comparing baseline reference days with nights of active ventilation and solar shading. Table 55 presents the temperature fluctuations (°C), relative humidity (%), and CO2 levels over three-hour intervals for both the reference and experimental conditions, involving natural Night Ventilation and Solar Shading RBB & ETC, are presented for the east-oriented living room (Liv.) and west-oriented bedroom (BRm.) in March and April 2024. Eq. 2 used to find the air temperature difference ($\Delta T_{air,\mathrm{EXP}}^{Room}$) with the action Night ventilation with Solar shading, Eq. 3 used to find the indoor air temperature °C difference with No Action at Experiment as baseline reference ($\Delta T_{air,\mathrm{REF}}^{Room}$). and Eq. 4 used to find the difference between the experiment (EXP) with action and no action (REF). The relative humidity (RH%) fluctuation at a set interval of 6 -hours is calculated using Eq. 7 for reference (REF) with no action ($\boldsymbol{\Delta\ RH}_{air,\mathrm{REF}}^{Room}$). Eq. 8 used to calculate with the action for the experiment (EXP) ($\boldsymbol{\Delta\ RH}_{air,\mathrm{EXP}}^{Room}$).

4.2.3 (i) An overview of temperature reduction potentials using natural night ventilation with Solar Shading strategies for transitional periods

Action natural Night ventilation and Solar Shading experiments (NV+SS) conducted at the BK living lab with the actions outlined below (Cf. Section 3.3.3, Figure 74, Table 16).

Exp. NV + SS

The experiments under passive conditions indicated a temperature reduction potential during the transitional season in March, with an average of 3°C achieved when the external temperature ranged from 18°C at 6 am to 36°C at noon. April, however, showed lower results, with an average of 1°C. As the external temperature rose, the indoor temperature also increased, leading to a smaller temperature difference between the outside and inside.

Table 38: The indoor air temperature (°C) reduction potentials $\Delta T^{Room}_{air,\ ACTION\ Benefits}$ *(cf. Section 3.6.1, Eq. 4) during winter and transitional season, between actions use of Night Ventilation and Solar Shading (NV+SS), and no natural ventilation.*

	Exp. NV + SS :RBB MAR 24		Exp. NV + SS : ETC APR 24	
	East	West	East	West
Natural Ventilation	**Liv.**	**BRm**	**Liv.**	**BRm**
Min	1	2	1	1
Max	6	5	2	2
Average	3	3	1	1

Table 38 illustrates the natural ventilation action of NV + SS under passive conditions, showing the potential to lower indoor temperatures by up to 5°C in east- and west-facing rooms. NV benefits from cooler nighttime temperatures, allowing free cooling through cross ventilation during winter when outdoor temperatures range from 16 to 20°C. The combination of NV + SS helps keep temperatures cool at night and works alongside SS during the day. Additionally, the thermal mass of the clay lining, tile cladding of the composite wall, and concrete floor help regulate indoor temperatures throughout the day. These effects are evident in data from actions taken during winter and transitional seasons.

4.3.2 (ii) Potential temperature reduction with the action: natural Night Ventilation & Solar Shading (NV+SS) during 48 hours of experiment

The experiments were conducted in March 2024, during the transitional season for action NV + SS at the BK living lab, using SS: RBB and SS: ETC. The March temperature ranged from 17°C

to 36°C, providing an opportunity to use cooler outdoor temperatures for comfort through natural ventilation when the outside temperature is between 15 °C and 23 °C.

Table 39 shows experiment data evaluated for the potential of natural ventilation during these comfortably cool hours and the use of solar shading as temperatures exceeded 24 °C. It included a baseline period of 2 days (48 hours) without ventilation or shading, which was then compared to the following 2 days (48 hours) with night ventilation and solar shading (NV+SS). The analysis in Table 55 (Refer to Appendix F) compares the differences between the baseline and experimental days. The potential for reducing temperature was assessed by comparing East- and West-facing rooms, taking into account both patio temperatures and outdoor conditions.

Table 39: The indoor air temperature (°C) reduction potentials $\Delta T^{Room}_{air,\ ACTION\ Benefits}$ *(cf. Section 3.6.1, Eq. 4) during the transitional season with action Night Ventilation (NV) + Solar Shading RBB in March for the East-oriented Living & West-oriented Bed Room.*

		Exp. NV + SS :RBB -MAR 24		**Exp. NV + SS :ETC -MAR 24**	
		East	West	East	West
Action	Natural Ventilation: NV +SS	**Liv.**	**BRm**	**Liv.**	**BRm**
T Benefit NV + SS	6:00	-2	-2	-3	-3
	12:00	-6	-5	-1	-1
	18:00	-3	-3	-2	-2
	0:00	-1	-2	-3	-3
	6:00	-2	-2	-2	-2
	12:00	-6	-5	-1	-2
	18:00	-3	-3	-1	-1
	0:00	-2	-2	3	3
	6:00	-2	-2	6	5
6.00 to 18.00 **day 1**	Max	-6	-5	-3	-3
	Min	-2	-2	-1	-1
	Average	-4	-4	-1	-1
6.00 to 18.00 **day 2**	Max	-6	-5	-2	-2
	Min	-2	-2	-1	-1
	Average	-4	-4	-1	-1

Table 55 (Appendix F) shows the external temperature at 18-36 °C in March 2024; a potential drop in indoor temperature of up to 5 to 6 °C is achieved with the NV + SS: RBB. The temperature drop was only 1 to 2 °C with NV + SS: ETC. The SS: RBB blocks direct sunlight hitting the glazing

facing the exterior, resulting in a better indoor temperature drop as the external temperature rises by 12 pm.

The indoor temperature on both experimental days shows a potential drop of 1 to 2 °C with NV. A temperature drop is observed from 6 am to 6 pm on both experimental days, demonstrating the potential of SS: RBB to reduce solar heat gain impact on the temperature rise outside and to retain the free cooling gained through natural ventilation, thanks to the thermal inertia properties of the clay lining tiles on the indoor walls and the concrete floor.

Fig. 113 shows a consistent indoor temperature of 25 to 27 °C was observed in Liv. on the Ref. Exp. Day when the outdoor temperature fluctuated between 18 and 32 °C. Fig. 114 shows the Experimental NV + SS: RBB shows a temperature reduction of 2 to 3 °C at 12 pm; indoors, the temperature was 24 to 25 °C while outside it reached 34 to 36 °C. (Refer Table 55, Appendix F)

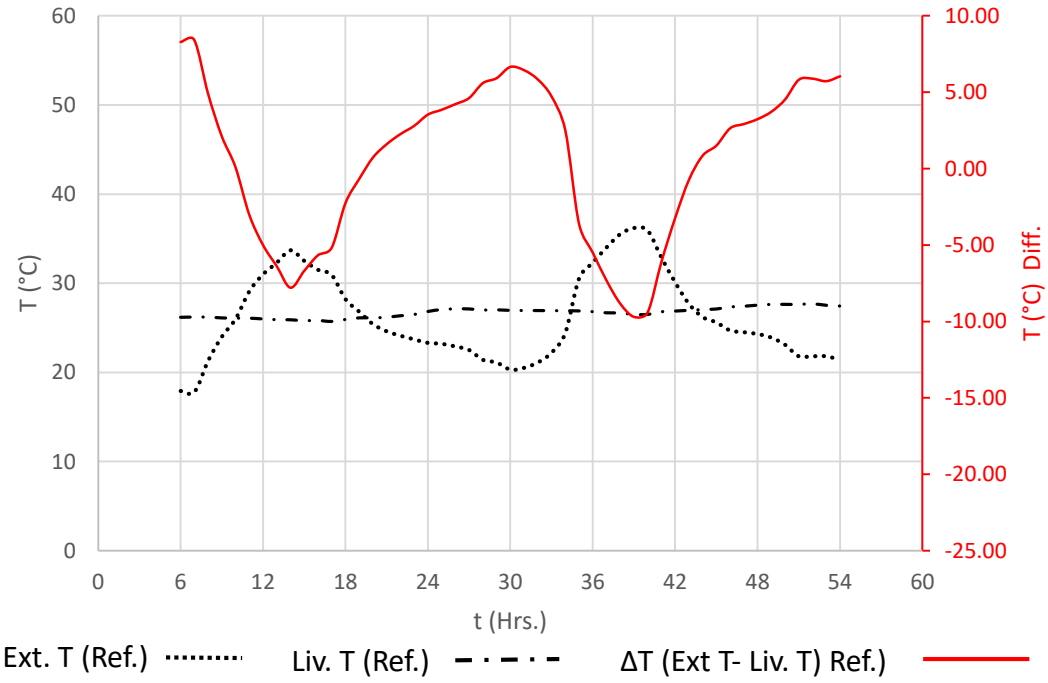


Figure 113: Comparison of indoor air temperature (°C) in Living (Liv.) , external (EXT) air temperature on reference (REF.) days in March

The indoor temperature drop between 6 am and 6 pm on both days of the Experimental NV + SS: RBB. The temperature rises by 2 °C at 12 am on both days of the Experimental NV + SS: RBB due to the thermal inertia of the envelope system, which slows the indoor temperature from

reaching that of the environment. The indoor temperature is 1°C higher than the outside temperature during the night from 12 am to 6 am. The temperature drops during the day without cross ventilation, while a consistent indoor temperature is maintained with SS: RBB. Comparison of indoor air temperature between Context (Con.), Patio (Pat.) & Liv on Ref. and Exp. NV + SS days in March 2024 as in Fig. 113 and 114.

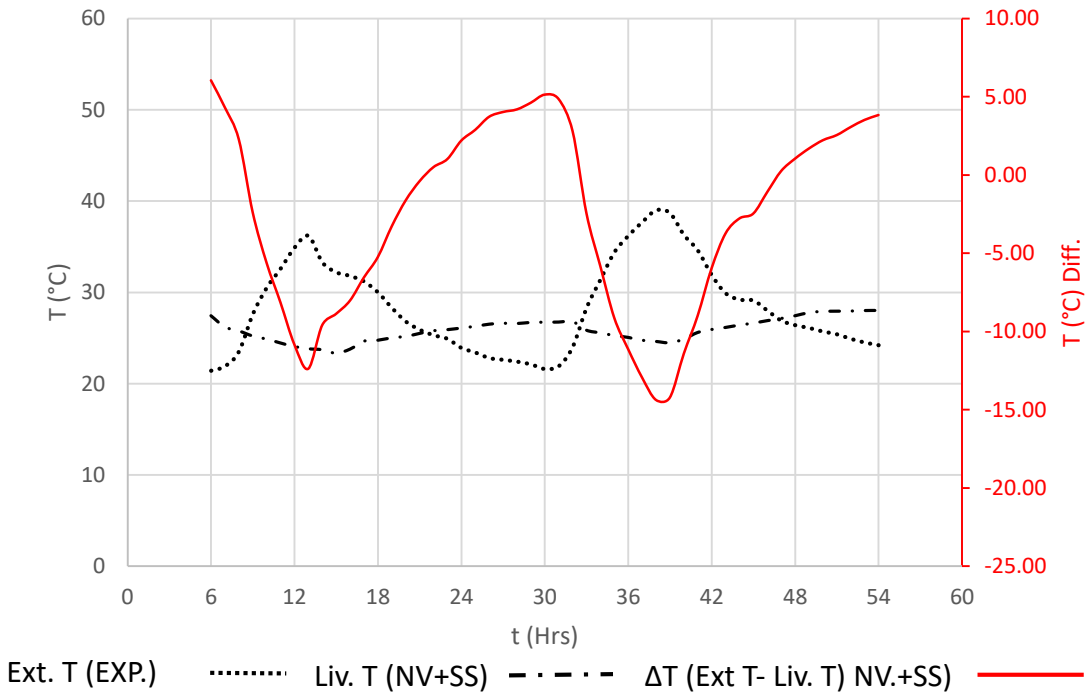


Figure 114: Comparison of indoor air temperature (°C) in Living (Liv.), external (EXT) air temperature on EXP. NV + SS day in March

- **Indoor air Temperature fluctuations at 3-hour intervals at Liv. & BRm during Exp. NV+SS: RBB days in March 2024**

Fig. 115 shows the indoor air temperature fluctuation at an interval of 6-hours, with the action of night ventilation and solar shading RBB. A rise of 1°C to 1.5°C is observed during the night ventilation duration from 18.00 hours in the evening to 6.00 hours early morning. An air temperature drop of 1.67°C in East oriented living and 1.38°C in West-oriented bed room is observed at 12.00 noon, This is achieved with solar shading RBB as the indoor air temperature was at 3.39°C in east-oriented living 3.08°C in the West-oriented bed room on the day 1 in Living with no action of solar shading. (Refer Table 56 , Appendix F)

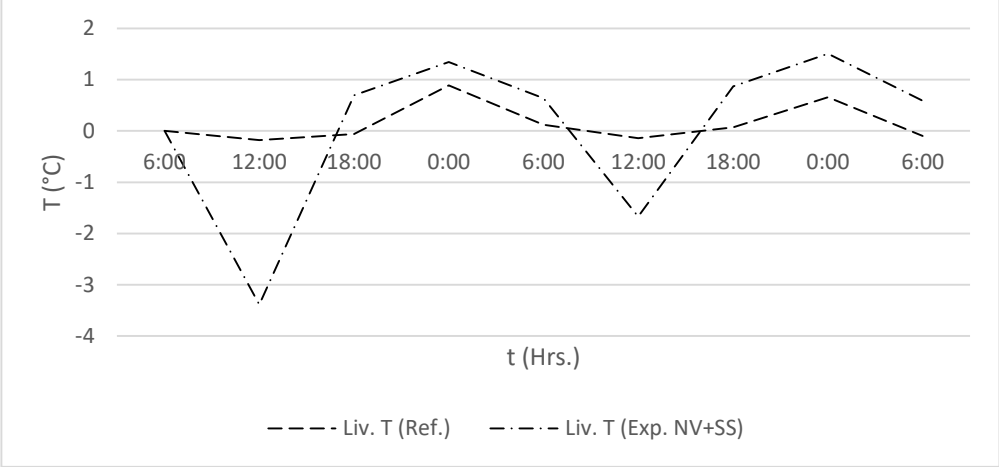


Figure 115: Comparison of indoor air temperature (°C) fluctuations in Living (Liv.) on Exp. NV + SS: RBB day in March

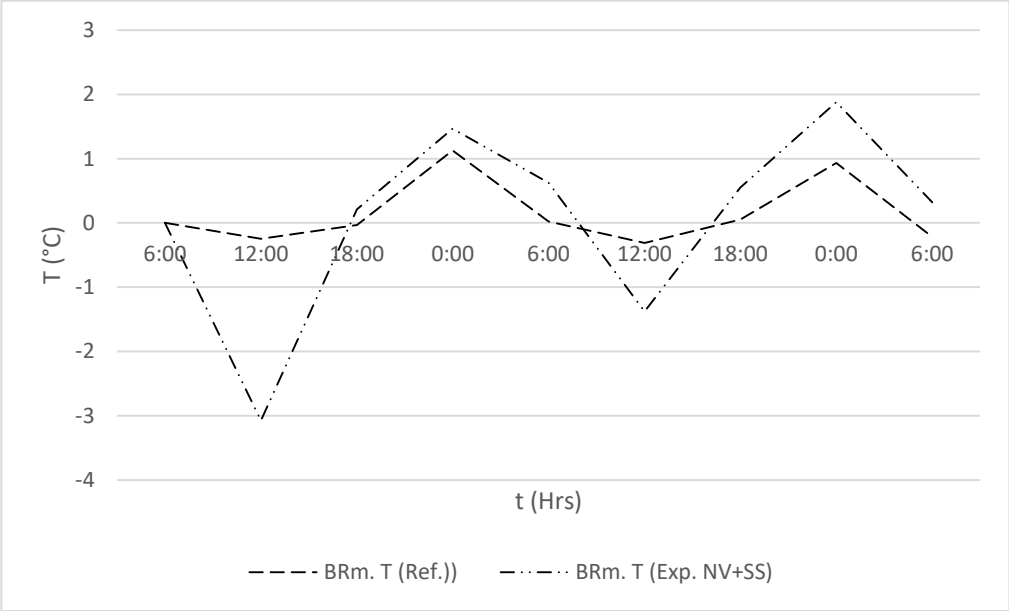


Figure 116: Comparison of indoor air temperature (°C) fluctuation in BRm (Ref.) & BRm. (Exp. NV + SS:RBB) day in March

Fig. 115 and Fig. 116 shows the comparison of indoor air temperature fluctuation between the East-oriented living and West-oriented bedroom between reference with the action NV+SS: RBB. The graphs show the same range of variation during the night, cress ventilation, and shading period. (Refer Table 56 , Appendix F)

Fluctuation in Relative Humidity (%) with action Exp. NV + SS RBB in East-Oriented Living. & West- Oriented Bedroom. in March 2024

Fig.117 and 118 shows the RH fluctuation comparison between the external RH (%) and the RH in East-oriented living and West-oriented bedroom with and without the action NV + SS RBB in March 2024. The comparison shows the external RH varying at a range of 20% to 75% . The indoor RH with no action was consistent at 56-57% in living and 64-67% in bedroom. The action NV+SS RBB shows no variation in RH with night ventilation when the variation at exteriors RH was 26%. The RH% during the non-cross ventilated hours in the day and with solar shading RBB showed an increase in RH by 3-4% at 12.00 hours on the day 2 of the experiment. The variation is very low and a consistent level maintained due to the thermal inertia properties of the clay lining tiles on the indoor walls being able to maintain with consistency indoors. (Refer Table 57, Appendix F)

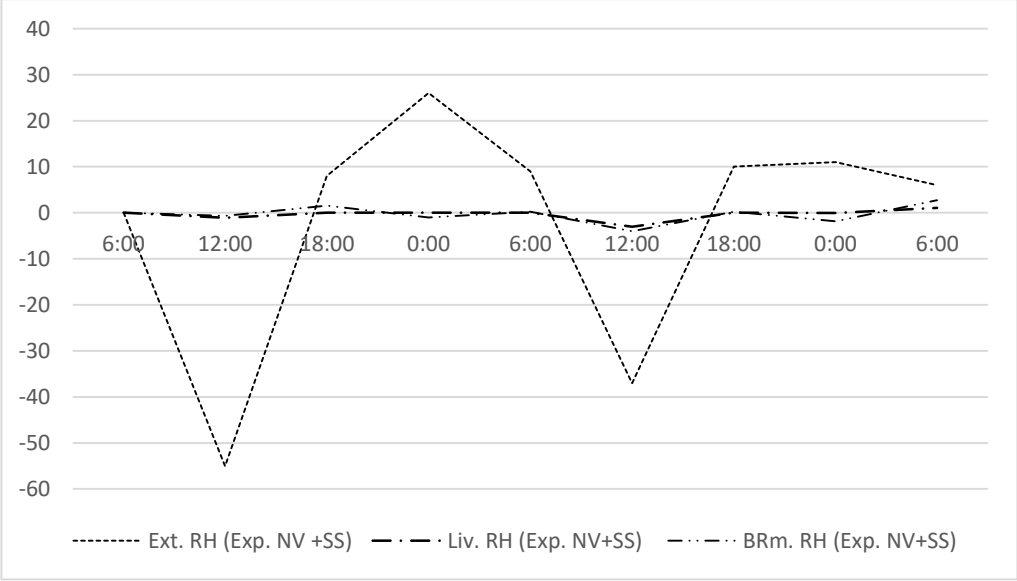


Figure 117: Comparison of RH (%) fluctuations between Ext. RH & Liv., BRm on (Exp. NV + SS:RBB) day in March

Fig.117 shows the RH (%) at the exterior in March 2024 with the fluctuation during the 48 hours experiment period. The indoor RH in the East-oriented and West-oriented room shows a consistency across the 48 hours of experiment with the action NV+SS RBB. The Fig.118 and Fig. 119 shows the RH (%) fluctuation in the living and bedroom with the action NV+SS RBB.

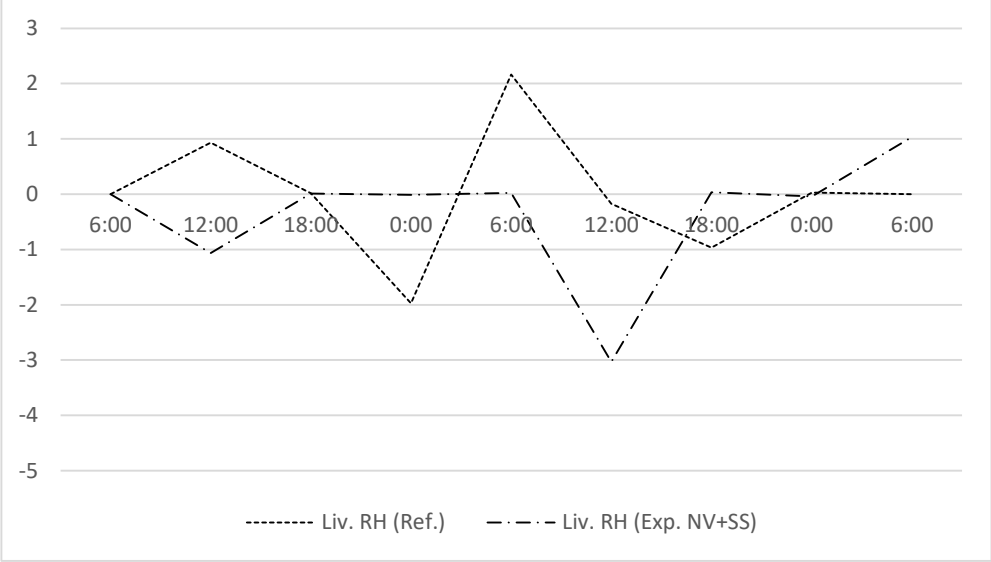


Figure 118: Comparison of RH (%) fluctuation between Liv. (Ref.) & Liv. (Exp. NV + SS: RBB) day in March

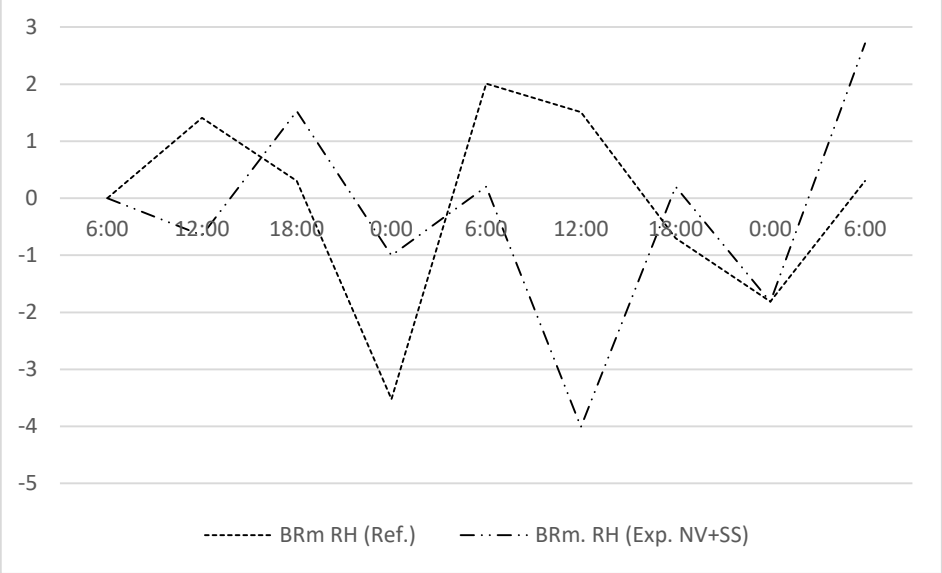


Figure 119: Comparison of RH (%) fluctuations between BRm. (Ref.) and BRm (Exp. NV + SS:RBB) day in March

The Fig. 118 and 119 shows the RH (%) fluctuation with the impact of NV between 18.00 and 6.00 and the RH (%) fluctuation shows 3% to 5% variation a drop in RH achieved with solar shading using RBB.

4.3.2 (iii) Summary for Experimental analysis of natural Night Ventilation and Solar Shading indoor effects

During the transitional season, the combined strategy of Natural Ventilation and Solar Shading is put to the test. It leverages Night Ventilation to tap into daily temperature fluctuations for free cooling in indoor spaces, and Solar Shading to reduce solar heat gain during the day. This extends the thermal comfort provided by free cooling to individual rooms within the experimental zone.

The natural ventilation action of NV + SS under passive conditions demonstrated the potential to lower indoor temperatures by 3 - 6°C in East- and West-oriented rooms. The NV benefits from cooler nighttime temperatures when external temperatures range from 16 to 20°C.

With the external temperature at 18-36 °C in March 2024; a potential drop in indoor temperature of up to 5 to 6 °C is achieved with the NV + SS: RBB. The indoor air temperature drop was only 1 to 2 °C with NV + SS: ETC.

The SS: RBB was more effective to blocks direct sunlight hitting the glazing facing the exterior, resulting in a better indoor temperature drop as the external temperature rises by 12 pm.

The thermal mass of the clay lining, tile cladding of the composite wall, and the concrete floor assist in regulating indoor temperatures throughout the day by 2-3°C in 24 hours interval (Refer Table 52, 53 and 54).

A consistent indoor temperature of 24°C to 28 °C was observed in Liv. and BRm with the action NV+SS in March 2024. The indoor temperature was at 26°C to 28 °C with no action on the reference experiment. The external air temperature was at 17°C - 36°C.

The RH was at 52 – 56% in East-oriented living and 61 – 65% in the West-oriented Bedroom with the action NV + SS, this was at the range 20 – 57% at the exteriors. With no action of NV +SS, the RH was 55 – 56% in East-oriented living and 64 – 67% in the West-oriented Bedroom. The cross ventilation could drop the RH % maintaining consistency with gradual variation of 1-2% in 6 hours interval.

4.2.4 Experimental analysis of Patio managing outdoor effects

4.2.4. (i) Patio Solar Shading action benefits

The patio (courtyard) at the center of the BK Lab connects the interiors of the living and bedroom areas to the outdoors. The architectural form and solar shading pergola provide shade over the patio to create a microclimate. The results of the patio shading experiment show differences in temperature and relative humidity compared to the external lab site measurements. Table 40 displays the data analyzed for the winter, summer, and transitional months regarding the changes in temperature (°C) achieved during the experimental period with no occupancy at the BK living lab.

Table 40: The indoor air temperature (°C) reduction potentials $\Delta T^{Patio}_{air,\ SHD_BENEFITS}$ *(cf. Section 3.6.2, Eq. 9) during the Peak Summer, Winter & Transitional season with architectural form Solar Shading Pergola.*

Patio Shading - Pat.Shd. - T (°C)								
Action		Time (Hrs.)	Jan	March	April	July	Aug	Sept
T (°C) Benefit with architectural form and solar pergola	Solar Period	6:00	-2	-2	-2	-2	-1	-1
		12:00	-3	-3	-1	-1	-1	-2
		18:00	-2	-2	-4	-3	-3	-2
	Night	0:00	-2	-3	-3	-2	-2	-2
	Solar Period	6:00	-1	-3	-2	-1	-2	-2
		12:00	-3	-3	0	-2	-1	-2
		18:00	-2	-3	-4	-3	-2	-2
	Night	0:00	-2	-2	-3	-2	-2	-2
	Early Morning	6:00	-1	-3	-2	-2	-1	-3
6.00-to-18.00-day **1**		Max	-3	-3	-4	-3	-3	-2
		Min	-2	-2	-1	-1	-1	-1
		Average	-2	-3	-2	-2	-2	-2
6.00-to-18.00-day **2**		Max	-3	-3	-4	-3	-2	-2
		Min	-1	-3	0	-1	-1	-2
		Average	-2	-3	-2	-2	-2	-2

Note: **(-Ve)** indicated the potential indoor air temperature °C reduction, **(+Ve)** indicated the potential indoor air temperature °C increase

Compared to the external environment, the patio temperature at 12 noon drops by 3°C in winter and by 1-2°C during transitional months and peak summer. At 18.00 hours, a consistent 2-3 °C difference exists across all seasons. At midnight, the patio also stays 2-3 °C cooler than outside.

The architectural design and solar shading pergola effectively block direct sunlight, as shown in Figure 120, which illustrates the patio's shade from sunrise to sunset. The patio remains shaded from sunrise until 11am and from 2pm until sunset due to its architectural proportions relative to its size. Additionally, the solar pergola increases shade over the patio, making it more comfortable.

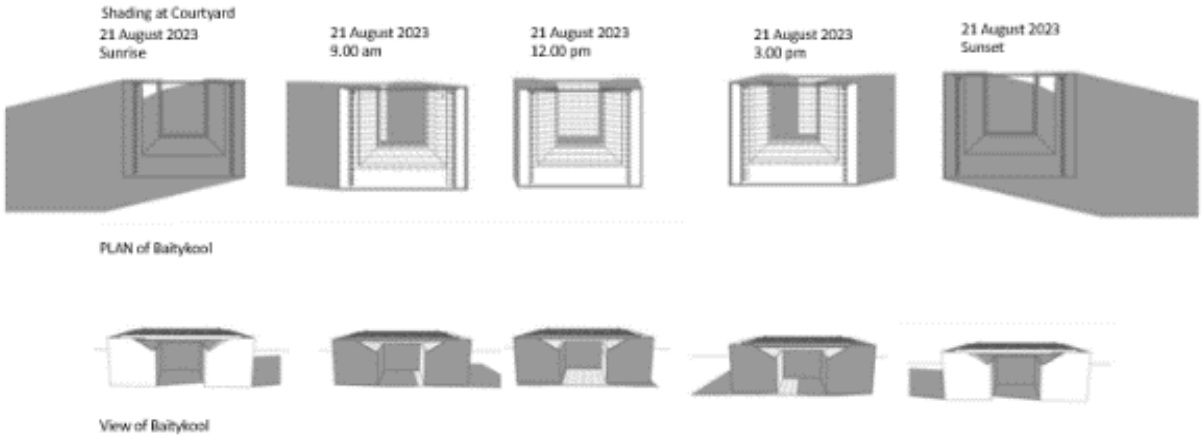
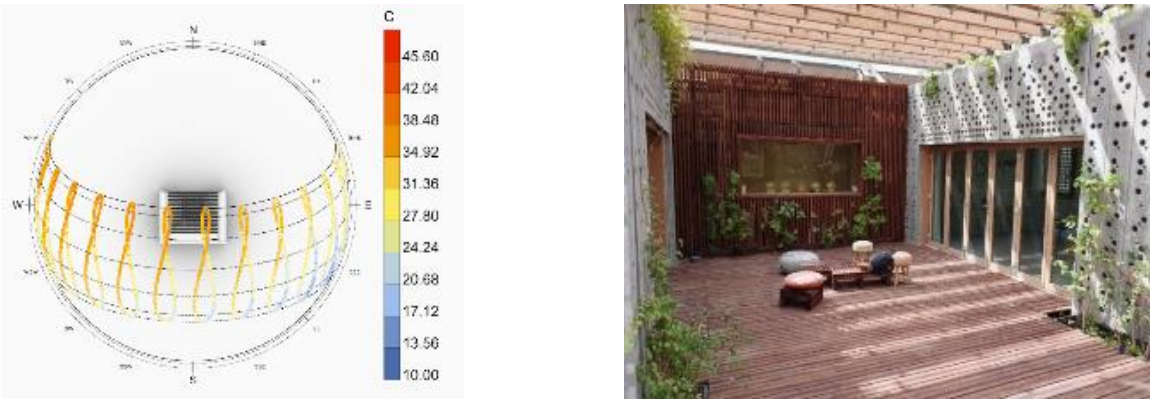


Figure 120: Patio shading at BaityKool prototype from sun rise to sunset in August

The architectural design helps reduce solar heat gain at the BK living lab patio. The patio, which faces north, allows maximum daylight without direct sunlight. The ratio of the patio size to the architectural form and its orientation, as shown in Fig. 121, takes advantage of the sun's path. Additionally, the solar pergola shades the patio from direct sunlight between 9 am and 4 pm, enhancing thermal comfort.



(a) (b)

Figure 121: (i) Sun path diagram in 12 months on BK lab with the average temperature (°C), (ii) BaityKool Patio shading at 11am in September

Table 41: Indoor air Temperature (°C) $\Delta T^{Patio}_{air,\ SHD_BENEFITS}$ *(cf. section 3.6.2, Eq 9) at 6-hour intervals during the at Patio during the winter and transitional season.*

	Winter			Transitional Season					
t	Context (T) 17 & 18 Jan 24	Patio (T) 17 & 18 Jan 24	Diff (T) at Patio 17 & 18 Jan 24	Context (T) 13 & 14 March 24	Patio (T) 13 & 14 March 24	Diff (T) at Patio 13 & 14 March 24	Context (T) 04 & 05 April 24	Patio (T) 04 & 05 April 24	Diff (T) at Patio 04 & 05 April 24
6:00	20.8	19.0	**-1.7**	17.9	16.0	**-1.8**	20.7	19.0	**-1.7**
12:00	29.9	27.1	**-2.7**	31.0	28.7	**-2.2**	32.7	32.1	**-0.6**
18:00	25.1	23.3	**-1.7**	28.2	26.1	**-2.0**	33.2	29.0	**-4.1**
0:00	22.8	20.9	**-1.8**	23.3	21.6	**-1.6**	24.3	21.5	**-2.8**
6:00	18.8	17.4	**-1.3**	20.3	18.7	**-1.5**	19.4	17.6	**-1.7**
12:00	28.6	26.0	**-2.5**	32.3	30.2	**-2.0**	33	33.0	**0.0**
18:00	25	23.1	**-1.8**	30.1	27.7	**-2.3**	32.2	28.2	**-4.0**
0:00	20.6	19.0	**-1.5**	24.3	22.4	**-1.8**	24.1	21.6	**-2.5**
6:00	18.6	17.1	**-1.4**	21.4	19.5	**-1.8**	19.6	17.6	**-2.0**

Note: **(-Ve)** indicated the potential air temperature °C reduction, **(+Ve)** indicated the potential air temperature °C increase

Table 42: Indoor air Temperature (°C) $\Delta T^{Patio}_{air,\ SHD_BENEFITS}$ *(cf. section 3.6.2, Eq 8) at 6-hour intervals during the at Patio during the Peak Summer season.*

	Peak Summer								
t	Context (T) 17 & 18 July 23	Patio (T) 17 & 18 July 23	Diff (T) at Patio 17 & 18 July 23	Context (T) 22 & 23 Aug 23	Patio (T) 22 & 23 Aug 23	Diff (T)at Patio 22 & 23 Aug 23	Context (T) 23 & 24 Sept 23	Patio (T) 23 &24 Sept 23	Diff (T) at Patio 23 &24 Sept 23
6:00	33.3	30.9	**-2.39**	30.7	29.7	**-0.93**	30.6	29.2	**-1.4**
12:00	46.4	45.0	**-1.33**	45.9	45.0	**-0.83**	46.6	44.2	**-2.3**
18:00	41.4	38.8	**-2.52**	40.3	37.5	**-2.78**	40.2	38.3	**-1.9**
0:00	35.5	33.7	**-1.71**	34.9	32.7	**-2.12**	34.4	32.3	**-2.0**
6:00	31.8	30.4	**-1.32**	31.8	30.2	**-1.60**	32.1	30.1	**-2.0**
12:00	46.6	44.8	**-1.71**	44.9	43.7	**-1.15**	45.1	43.5	**-1.5**
18:00	40.6	37.9	**-2.70**	40.2	37.9	**-2.30**	40	37.6	**-2.3**
0:00	35.3	33.7	**-1.54**	35.2	33.4	**-1.72**	34.9	33.0	**-1.8**
6:00	33	31.4	**-1.56**	33.1	31.6	**-1.48**	31.8	29.2	**-2.6**

Note: **(-Ve)** indicated the potential air temperature °C reduction, **(+Ve)** indicated the potential air temperature °C increase

The patio RH (%) at 10-15% higher than exterior context across the winter, transitional & summer season as indicated in Table 43.

Tables 44 and 45 illustrate the difference in relative humidity (RH %) between the outdoor environment and the patio across the seasons. At 12 noon, RH is 40-50% in winter, 25-35% during the transitional season, and 15-30% in summer. By 6pm, RH increases to 50-60% in winter, 40-55% during the transitional season, and 40-60% in summer.

Rising temperatures decrease the RH %. The presence of vegetation in the patio, roof, and aquaponic system results in a wider RH% range compared to the outdoor environment. During peak summer in August, a 15% RH was observed indoors when the outdoor RH was 1-5%, with outdoor temperatures ranging from 40 to 47 degrees.

Table 43: Relative Humidity (%) $\Delta RH^{Patio}_{air,\ SHD\ BENEFITS}$ (cf. section 3.6.2, Eq 10) at 6-hour intervals during the at Peak Summer, Winter & Transitional season.

Patio Shading - Pat.S - RH (%)								
Action		Time (Hrs.)	Jan	March	April	July	Aug	Sept
RH % on Exp with Patio Shading using architectural form and solar pergola	Solar Period	6:00	14	15	11	13	6	10
		12:00	10	10	7	11	11	14
		18:00	10	9	17	12	12	10
	Night	0:00	11	13	15	11	12	14
	Solar Period	6:00	12	17	15	11	12	11
		12:00	13	13	5	15	9	14
		18:00	11	11	15	13	12	11
	Night	0:00	12	14	15	10	11	14
	Early Morning	6:00	12	16	12	11	11	14
6.00 to 18.00 **day 1**		Min	10	9	7	11	6	10
		Max	14	17	17	13	12	14
		Average	11	13	13	11	10	12
6.00 to 18.00 **day 2**		Min	11	11	5	10	9	11
		Max	13	17	15	15	12	14
		Average	12	14	12	12	11	13

Note: **(-Ve)** indicated the potential RH (%) reduction, **(+Ve)** indicated the potential RH (%) increase

Table 44: Relative Humidity (%) $\Delta RH^{Patio}_{air,\ SHD\ BENEFITS}$ (cf. section 3.6.2, Eq 9) at 6-hour intervals during the at Winter & Transitional season.

	Winter			Transitional Season					
t	Context (RH) 17 & 18 Jan 24	Patio (RH) 17 & 18 Jan 24	Diff (RH) at Patio 17 & 18 Jan 24	Context (RH) 13 & 14 March 24	Patio (RH) 13 & 14 March 24	Diff (RH) at Patio 13 & 14 March 24	Context (RH) 04 & 05 April 24	Patio (RH) 04 & 05 April 24	Diff (RH) at Patio 04 & 05 April 24
6:00	77	91	**14**	69	84	**15**	59	70	**11**
12:00	32	42	**10**	25	35	**10**	19	26	**7**
18:00	44	54	**10**	45	54	**9**	27	44	**17**
0:00	50	61	**11**	72	85	**13**	66	81	**15**
6:00	62	74	**12**	77	94	**17**	78	93	**15**
12:00	38	51	**13**	18	31	**13**	21	26	**5**
18:00	50	61	**11**	38	49	**11**	34	49	**15**
0:00	63	75	**12**	73	87	**14**	63	78	**15**
6:00	72	84	**12**	75	91	**16**	64	76	**12**

Note: **(-Ve)** indicated the potential RH (%) reduction, **(+Ve)** indicated the potential RH (%) increase

Table 45: Relative Humidity (%) $\Delta RH^{Patio}_{air,\ SHD\ BENEFITS}$ (cf. section 3.6.2, Eq 9) at 6-hour intervals during the Peak Summer season.

	Peak Summer								
t	Context (RH) 17 & 18 July 23	Patio (RH) 17 & 18 July 23	Diff (RH) at Patio 17 & 18 July 23	Context (RH) 22 & 23 Aug 23	Patio (RH) 22 & 23 Aug 23	Diff (RH) at Patio 22 & 23 Aug 23	Context (RH) 23 & 24 Sept 23	Patio (RH) 23 & 24 Sept 23	Diff (RH) at Patio 23 & 24 Sept 23
6:00	35	48	**13**	66	72	**6**	64	74	**10**
12:00	20	31	**11**	11	22	**11**	5	19	**14**
18:00	33	45	**12**	40	52	**12**	31	41	**10**
0:00	62	73	**11**	67	79	**12**	15	29	**14**
6:00	70	81	**11**	75	87	**12**	19	30	**11**
12:00	11	26	**15**	26	35	**9**	1	15	**14**
18:00	47	60	**13**	45	57	**12**	28	39	**11**
0:00	61	71	**10**	68	79	**11**	13	27	**14**
6:00	71	82	**11**	76	87	**11**	10	24	**14**

Note: **(-Ve)** indicated the potential RH (%) reduction, **(+Ve)** indicated the potential RH (%) increase

- The patio microclimate experienced a temperature decrease of 2-3°C compared to the outdoor environment throughout the year.
- A 10-15% higher relative humidity (RH) at the patio compared to the exterior environment.

- The shaded patio felt cooler to the human body than the actual air temperature outside, where there was no shade and it was directly exposed to the sun's rays.
- The T at the patio increases as the T at the exterior rises, but the solar shading from the architectural form and solar pergola prevents the patio from overheating and reduces glare.
- The wooden patio floor, which has low thermal conductivity and functions as a natural insulator, does not serve as a thermal break between the structure and the external envelope system.
- During the experimental period, the vegetation on the biological filter bed and wooden claustra wall (mashrabiya) facing north was sparse and in the growth stage. Denser vegetation could enhance thermal comfort through evapotranspiration.

4.2.4 (ii) Experimental at Patio Shading outdoor effect with and without the Solar Shading Pergola

The impact of solar shading on air temperature at the Patio of the BK prototype is demonstrated in Table 64, both with and without the use of the Solar Shading Pergola for the 48 hours of experiment duration in May 2024.

Table 64 shows a 3.32°C rise in air temperature at the Patio at 12.00 noon without the solar shading pergola. The air temperature at the Patio showed a difference of only 0.85°C with the use of the solar shading pergola at 12.00 noon. At 18.00 hours (evening) the difference observed was only 0.4°C due to the radiant heat from the surfaces around the patio leading to the temperature rise.

The impact of solar shading on RH at the Patio of the BK prototype is demonstrated in Table 65, both with and without the use of the Solar Shading Pergola for the 48 hours of experiment duration in May 2024.

Table 46:Difference in Patio air Temperature (°C) $\boldsymbol{\Delta T}^{\boldsymbol{Patio}}_{\boldsymbol{air,\ SHD_BENEFITS}}$ *(cf. section 3.6.2, Eq. 9) at 6-hour intervals during the Exp. Ref. with Solar Shading Pergola (WSSP) & Exp. Pat.SSP without solar shading pergola (WOSSP) for 48 hours*

	With Solar Shading Pergola			Without Solar Shading Pergola			
t	**Ref. Con. (T) WSSP 24/05/24**	**Ref. Pat. (T) WSSP 24/05/24**	**Diff (T) WSSP 24/05/24**	**Exp. Con. (T) WOSSP 29/05/24**	**Exp. Pat. (T) WOSSP 29/05/24**	**Diff (T) WOSSP 29/05/24**	**Diff (T) WOSSP 29/05/24**
06:00	26.4	24.8	**1.5**	27.8	26.0	**1.7**	**-0.1**
12:00	42.1	41.2	**0.8**	40.8	44.1	**-3.3**	**2.4**
18:00	38.4	35.2	**3.1**	42.9	39.3	**3.5**	**-0.3**
00:00	32.1	29.2	**2.8**	34.4	31.8	**2.5**	**0.2**
06:00	26.7	25.1	**1.5**	29.1	27.0	**2.0**	**-0.5**

Table 47 shows the RH at the exterior and at the Patio at the same range at 12.00 noon with 24% and 27% without the solar shading pergola. With the use of a solar shading pergola, the patio shows a difference of 11% to 13%.

The solar shading pergola enables a benefit in air temperature reduction up to 2.5% when compared with external temperature and also influences the reduction in RH % at 12.00 noon. The shaded environment at the patio creates a better thermal comfort condition when compared to the external environment.

Table 47:Difference in Patio RH (%) $\boldsymbol{\Delta\, RH}^{\boldsymbol{Patio}}_{\boldsymbol{air,\ SHD\ BENEFITS}}$ *(cf. section 3.6.2, Eq. 10) at 6-hour intervals during the Exp. Ref. with Solar Shading Pergola (WSSP) & Exp. Pat.SSP without solar shading pergola (WOSSP) for 48 hours*

	With Solar Shading Pergola			Without Solar Shading Pergola			
t	**Ref. Con. (RH) WSSP 24/05/24**	**Ref. Pat. (RH) WSSP 24/05/24**	**Diff (RH) WSSP 24/05/24**	**Exp. Con. (RH) WOSSP 29/05/24**	**Exp. Pat. (RH) WOSSP 29/05/24**	**Diff (RH) WOSSP 29/05/24**	**Diff (RH) WOSSP 29/05/24**
06:00	58	69	**-11**	79	92	**-13**	**2**
12:00	17	30	**-13**	24	27	**-3**	**-10**
18:00	31	42	**-11**	29	41	**-12**	**1**
00:00	53	68	**-15**	54	68	**-14**	**-1**
6:00	65	74	**-9**	77	91	**-14**	**5**

4.2.4 (iii) Summary for Experimental analysis of Patio managing outdoor effects

Compared to the external environment, the patio temperature at 12 noon drops by 3°C in winter and by 1-2°C during transitional months and peak summer. At 18.00 hours, a consistent 2-3°C

difference observed across all seasons. At midnight, the patio also remains 2-3°C cooler than exterior temperature at the BK living lab context location.

The architectural design and solar shading pergola effectively block direct sunlight, with the ratio of the patio size to the architectural form and its orientation, as shown in Figs. 102 and 121, showing the advantage of the orientation of the BK prototype and the sun's path.

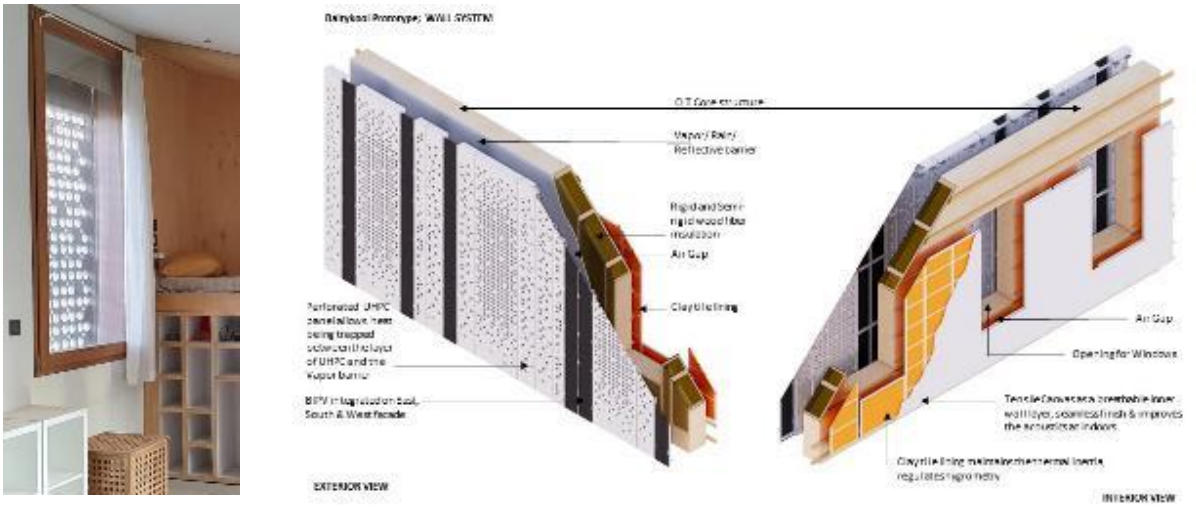
The RH (%) at the patio was observed to be 10-15% higher than the exterior throughout winter, transitional, and summer seasons (Refer Table 62). The presence of vegetation in the patio, roof, and aquaponic system results in a higher RH% range compared to the outdoor environment.

The solar shading pergola could reduce air temperature at Patio by 3°C and maintain the RH at 10% higher level than the exterior RH levels. The shaded patio felt cooler to the human body than the actual air temperature outside with no shade, and being directly exposed to the sun's rays.

4.3 The performance of the envelope system at BaityKool prototype

The experiment evaluates the ability of the multilayer high-performance wall composition of the Envelop system in the BaityKool prototype to resist external heat.

At the walls, the external porous UHPC layer of the envelope system protects all the glazed external windows from direct sunlight and UV rays, as shown in Fig. 122 (a). It allows light to enter the interior while maintaining visual privacy for indoor spaces. The air gap between the UHPC panel and the vapor barrier membrane of the exterior wall insulation system, as depicted in Fig. 122 (b), enables heat to dissipate and reduces heat transfer through conduction.



(a) (b)

Figure 122: (a) Image of the external porous UHPC layer acting as a shading screen for the double glazing, (b) The multilayered high-performance Wall composition of the Envelop system

The tough UHPC panel acts as a strong protective shield against hot weather, with temperatures reaching up to 51°C in August. It absorbs cold at night and radiates it inward as daytime temperatures rise, warming the UHPC. When outside temperatures fall at night, the thermal inertia of the insulation gradually releases heat into the indoor space, raising the indoor temperature and keeping the area warm and comfortable. The temperature increase is gradual, between 1 and 3 °C.

4.3.1 The indoor air temperature benefits achieved with the performance of the envelope system at BaityKool

The benefits of indoor air temperature (°C) reduction achieved by the envelope system throughout the year during the experimental period are outlined below in Table 48. Table 68 shows that a higher air temperature reduction potential of 14 to 19 °C is observed in August, the peak summer month, when temperatures can reach up to 46°C. Table 49 shows that in January, a 9°C reduction occurs at noon, with night temperatures dropping to 20°C, resulting in a steady indoor temperature of 22 to 24°C under passive conditions without air conditioning. During March and April 2024, temperatures fluctuate between 18 and 33.5°C, while indoor temperatures stay steady at 26 to 28°C. Table 66 demonstrates that in summer, temperatures range from 33 to 51°C at noon and drop to about 35°C at midnight. Indoor temperatures are reduced by 10 to 14°C, maintaining a consistent range of 27 to 31°C

Table 48: The indoor air temperature benefit $\Delta T_{air,\ N,\ SHD}^{Room}$ (cf. Section 3.6.3, Eq. 10) during peak summer, winter & transitional season with no-use of Solar Shading Curtain for the external facing glazed windows and doors

BK Envelope system performance - T (°C)								
Months			Winter	Transitional Season		Peak Summer		
			Jan	March	April	July	Aug	Sept
Parameters		Time (Hrs.)	T (°C) benefit	T (°C) benefit	T (°C) benefit	T (°C) benefit	T (°C) benefit	T (°C) benefit
T (°C) Benefit with the composite envelope system	Solar Period	6:00	7	8	6	1	-3	-2
		12:00	-9	-5	-7	-10	-19	-13
		18:00	-6	-2	-6	-5	-11	-9
	Night	0:00	4	4	3	1	-5	-4
	Solar Period	6:00	8	7	6	5	-1	0
		12:00	-5	-5	-7	-10	-14	-14
		18:00	-3	-3	-6	-4	-10	-8
	Night	0:00	3	3	2	-1	-6	-5
	Early Morning	6:00	3	6	7	0	-3	0
6.00 to 18.00 **day 1**		Max	-10	-5	-7	-10	-19	-13
		Min	5	8	6	5	-1	0
		Average	-2	2	0	-2	-8	-6
6.00 to 18.00 **day 2**		Max	-10	-5	-7	-10	-14	-14
		Min	5	7	6	5	-1	0
		Average	-2	1	1	-2	-7	-5

Note: **(-Ve)** indicated the potential indoor air temperature °C reduction, **(+Ve)** indicated the potential indoor air temperature °C increase

The details of the indoor air temperature reduction potential without any actions throughout the experiment duration in Winter and Transition season are shown in Table 49, and for the peak Summer in Table 50. The difference between the external temperature at the BaityKool living lab site and the indoor air temperature in the living area of the BaityKool living lab, with no action, compared to the impact of the envelope system under passive conditions and with no occupancy at the living lab.

Table 49 shows that the indoor air temperature at BaityKool living lab ranged from 23°C to 26.5°C during the January 2024 Winter season.

Table 49: Indoor air Temperature (°C) $\Delta T_{air,\ N,\ SHD}^{Room\ \ DATE/MONTH}$ (cf. section 3.6.3, Eq10) at 6-hour interval when External T(°C) is compared with the baseline Reference in Winter and Transitional Season

	Winter			Transitional Season					
	Jan.			Mar.			April		
t (hrs.)	Ref. Ext. T(°C) 15& 16 Jan	Ref. Liv. T(°C) 15 & 16 Jan	Diff T(°C) 15 & 16 Jan	Ref. Ext. T(°C) 13 & 14 Mar. 24	Ref. Liv. T(°C) 13 & 14 Mar. 24	Diff T(°C) Liv. 13 & 14 Mar. 24	Ref. Ext. T(°C) 02 & 03 April 24	Ref. Liv. T(°C) 02 & 03 April 24	Diff T(°C) Liv. 02 & 03 April 24
6:00	16.6	23.1	**7**	17.9	26.1	**8**	19.6	25.5	**6**
12:00	32	22.9	**-9**	31	26.0	**-5**	32	25.2	**-7**
18:00	28.5	22.8	**-6**	28.2	25.9	**-2**	31.5	25.6	**-6**
0:00	20.1	23.8	**4**	23.3	26.8	**4**	24.1	26.8	**3**
6:00	16.6	24.3	**8**	20.3	26.9	**7**	20.8	26.9	**6**
12:00	29.8	24.4	**-5**	32.3	26.8	**-5**	33.6	26.8	**-7**
18:00	27.5	24.4	**-3**	30.1	26.8	**-3**	32.3	26.5	**-6**
0:00	23.3	26.4	**3**	24.3	27.5	**3**	25.8	27.8	**2**
6:00	20.8	23.9	**3**	21.4	27.4	**6**	20.7	27.9	**7**

Note: **(-Ve)** indicated the potential indoor air temperature °C reduction, **(+Ve)** indicated the potential indoor air temperature °C increase

A maximum air temperature reduction potential of 9°C was observed at 12.00 noon with no action. The indoor air temperature in the lab living room was 24°C when the external temperature lowered to 16.6°C, and was at 22.84°C at 18.00 hours (evening) when the external temperature rose to 28.5°C. The transitional season also achieved an indoor air temperature reduction potential of 7°C when the external temperature rose to 32°C. at 12.00 noon. The indoor air temperature was consistent at a range of 25°C on Day 1 of the experiment and rose to 28°C on Day 2, with the BK living lab kept closed with no cross ventilation and no action of the dynamic solar shading curtain. The external temperature was at a range of 19.6°C to 33.6°C, the envelope system could manage to maintain a consistent indoor air temperature of 25°C to 28°C.

The table 50 indicates that indoor air temperature reached 51°C on the hottest days of August, while the indoor air temperature stayed steady at 28-29°C over the two days (48 hours) of the experiment.

Table 50: Indoor air Temperature (°C) $\Delta T_{air,\ N,\ SHD}^{Room\ \ DATE/MONTH}$ (cf. section 3.6.3, Eq10) at 6-hour interval when External T(°C) is compared with the baseline Reference in Peak Summer Season

	Peak Summer								
	July			August			Sept.		
t (hrs.)	Ref. Ext. T(°C) 17 & 18 July 23	Ref. Liv. T(°C) 17 & 18 July 23	Diff T(°C) Liv. 17 & 18 July 23	Ref. Con. T)(°C) 22 & 23 Aug. 23	Ref. Liv. T (°C) 22 & 23 Aug. 23	Diff T(°C) Liv. 22 & 23 Aug. 23	Ref. Con. T(°C) 20 & 21 Sept. 23	Ref. Liv. T(°C) 20 & 21 Sept. 23	Diff T(°C) Liv. 20 & 21 Sept. 23
6:00	33.3	33.9	**1**	30.7	27.5	**-3**	33.7	31.6	**-2**
12:00	46.4	36.4	**-10**	45.9	27.3	**-19**	44.8	31.4	**-13**
18:00	41.4	36.1	**-5**	40.3	28.9	**-11**	39.6	30.6	**-9**
0:00	35.5	36.0	**1**	34.9	29.4	**-5**	34.1	30.2	**-4**
6:00	31.8	36.3	**5**	31.8	30.9	**-1**	30.8	31.1	**0**
12:00	46.6	37.0	**-10**	44.9	30.7	**-14**	44.6	31.0	**-14**
18:00	40.6	36.1	**-4**	40.2	29.8	**-10**	38.8	30.3	**-8**
0:00	35.3	34.3	**-1**	35.2	29.6	**-6**	34.4	29.6	**-5**
6:00	33	33.3	**0**	33.1	30.3	**-3**	30.6	30.3	**0**

Note: **(-Ve)** indicated the potential indoor air temperature °C reduction, **(+Ve)** indicated the potential indoor air temperature °C increase

Table 50 shows that the BK envelope system achieves an 18°C reduction in indoor air temperature, and this reduction increases further with the use of the Solar Shading device RBB. An air temperature difference of 22°C indoors was recorded at noon under passive conditions. When the exterior temperature rose to 51°C, the indoor air temperature was 28.5°C. The indoor air temperature drops during the day, reaching its lowest point by noon, while the outside temperature increases. Conversely, at night, the temperature rises, peaking at midnight as the outside temperature drops. Nonetheless, the temperature varies by about 3°C, maintaining a steady indoor air temperature even when outside temperature fluctuates between 14-15°C.

Table 51 illustrates the BK envelope system as a robust protective barrier, capable of achieving temperature reductions of up to 10°C during the hot summer months. In winter, it allows decreases of up to 9°C, and during transitional seasons, it provides reductions of 5-7°C. A consistent indoor temperature of 2-3°C was kept throughout the 48-hour experiment under passive, unoccupied

conditions. The layers and material properties of the envelope systems caused a delay in indoor temperature reaching equilibrium due to thermal inertia.

Table 51: BK Envelope system performance with the difference T (°C) between the External context & indoor of BK lab during the hottest days of August month

t	Ref. Ext. T(°C) 22 & 23 Aug. 23	Ref. Liv. T(°C) 22 & 23 Aug. 23	Diff T(°C) Liv. 22 & 23 Aug. 23	Exp. Ext. T(°C) 25 & 26 Aug. 23	Exp. Liv. T(°C) 25 & 26 Aug. 23	Diff T(°C) 25 & 26 Aug. 23	Diff T (°C) Liv. 25 & 26 Aug. 23 (Exp. SS:RBB)
6:00	30.7	27.5	**-3.12**	35.0	28.8	**-6.13**	**-3**
12:00	45.9	27.3	**-18.54**	51.1	28.5	**-22.5**	**-4**
18:00	40.3	28.9	**-11.36**	41.4	29.9	**-11.4**	**0**
0:00	34.9	29.4	**-5.49**	36.9	29.2	**-7.6**	**-2**

Note: **(-Ve)** indicated the potential indoor air temperature °C reduction, (**+Ve)** indicated the potential indoor air temperature °C increase

4.3.2 Experimental analysis of BK envelope regarding indoor Moisture content benefits

The relative humidity (RH) measures the amount of moisture in the air at a specific temperature, expressed as a percentage of the maximum possible moisture at saturation. Absolute humidity (AH), measured in grams of water per cubic meter of air (g/m³), shows the amount of water vapor present in the air. Understanding both types of humidity helps improve indoor air quality and thermal comfort. AH directly indicates the water vapor content, with higher values meaning more moisture. AH stays the same even if the temperature (T) increases or decreases. RH rises when the temperature drops and falls when the temperature rises. AH provides a direct measure of moisture, while RH shows how saturated the air is relative to its temperature. A relative humidity (RH) range of 40-60% is recommended for good thermal comfort and health [67]. Below 40% RH, the air feels too dry, causing discomfort such as dry skin and respiratory irritation. Above 60% RH, the air feels sticky and uncomfortable, increasing the risk of condensation and mold growth. An optimal absolute humidity (AH) range of 6–12 g/m³ is suggested for thermal comfort. Below 6 g/m³, the air is too dry and uncomfortable, while above 12 g/m³, the air feels excessively moist.

Peak Summer

The Table 52 shows the AH range during peak summer months under passive conditions with a neural reference (Ref.) and no actions taken was high, ranging from 20-31 g/m³ in July, 18-24 g/m³ in August, and 17-22 g/m³ in September. Implementing Solar Shading with Roller Blind Blackout (SS:RBB) reduced the AH by 2-7 g/m³ across July, August, and September. In July, the AH in the west-oriented bedroom (BRm.) was higher by 2-5 g/m³ compared to the east-oriented living room (Liv.) because this month involved an experiment with a single occupant. The occupant used the BRm for both living and working more often than the living room, and access to the exterior patio was mostly from the bedroom, leading to a higher AH in the BRm. Comparing July to August 2023, the latter showed a consistent AH range of 18-21 g/m³ in both the Liv. and BRm., with experiments performed as planned and no occupancy. September also shows the west-oriented BRm with 2-5 g/m³ higher AH than the east-oriented Living.

Table 52: AH at BK experimental zones in peak summer months (cf. Section 3.6.5, Eq. 12)

Time (hrs.)	AH (g / m3)											
	PEAK SUMMER											
	JULY				AUGUST				SEPT.			
	N - Ref		EXP - SS:RBB		N - Ref		EXP SS:RBB		N - Ref		EXP - SS:RBB	
	Ref. Liv.	Ref. BRm.	Liv.	BRm.	Ref. Liv.	Ref. BRm.	Liv.	BRm.	Ref. Liv.	Ref. BRm.	Liv.	BRm.
	EAST	WEST	EAST	WEST	EAST	WEST	EAST	WEST	EAST	WEST	EAST	WEST
6:00	20	25	18	23	19	19	21	20	18	21	15	18
12:00	24	29	18	23	18	18	20	19	18	22	16	20
18:00	24	28	19	24	21	20	23	22	17	21	15	17
0:00	24	29	18	23	21	22	21	21	17	20	14	17
6:00	24	29	18	22	24	21	20	20	18	22	13	16
12:00	25	30	21	23	24	21	18	18	18	22	15	18
18:00	26	31	20	25	22	24	21	20	17	21	13	16
0:00	24	29	20	25	22	23	20	19	17	20	13	15
6:00	23	28	20	25	23	22	18	18	18	22	15	18

The indoor AH levels in January stay within a comfortable range of 6-12 g/m³. During the DV & NV experiment, cross ventilation causes lower AH levels in the living room (Liv.) and bedroom (BRm.) compared to the AH level on the reference (Ref.) day when there is no cross ventilation. The Table 71 shows AH remains steady between 10-12 g/m³ in the Liv. and 12-14 g/m³ in the BRm. In March, the indoor AH levels increase to 12-15 g/m³ in the Liv. and 14-17 g/m³ in the BRm. The east-facing Liv. shows an AH level 2 g/m³ lower than the west-facing BRm. A decrease

of 1 g/m³ in AH is observed with the night ventilation and solar shading actions (NV + SS: RBB) compared to the Ref. day with no cross ventilation or solar shading. In April, the AH stays within a comfortable range at 11 g/m³ during the first 24 hours of the experiment with the NV + SS: RBB actions. The indoor AH level remains steady at 12-13 g/m³ in the Liv. and 15 g/m³ in the BRm, with a 3 g/m³ difference in the Liv. and 15 g/m³ in the BRm.

Table 53: AH at BK experimental zones in winter and transitional months (cf. Section 3.6.5, Eq. 12)

Time (hrs.)	AH (g / m3)											
	WINTER				TRANSITIONAL SEASON							
	JAN.				MARCH				APRIL			
	N - Ref		EXP - DV + NV		N - Ref		EXP - NV+SS RBB		N - Ref		EXP - NV	
	Ref. Liv.	Ref. BRm.	Liv.	BRm.	Ref. Liv.	Ref. BRm.	Liv.	BRm.	Ref. Liv.	Ref. BRm.	Liv.	BRm.
	EAST	WEST	EAST	WEST	EAST	WEST	EAST	WEST	EAST	WEST	EAST	WEST
6:00	11	12	11	13	14	16	15	17	13	15	14	16
12:00	10	12	10	12	14	16	12	14	13	15	11	13
18:00	10	12	10	12	14	16	12	15	12	14	11	13
0:00	11	14	11	13	14	17	13	16	12	15	12	15
6:00	12	14	11	13	15	17	14	17	13	15	13	15
12:00	12	14	11	13	15	17	12	14	13	16	13	15
18:00	13	15	11	13	15	17	13	15	13	14	13	15
0:00	10	12	12	14	15	17	14	16	12	15	12	15

Extended exposure to the afternoon sun in west-facing rooms causes them to stay warmer because of solar radiation and heat gain. These rooms' interiors begin to warm up significantly by evening as the outside temperature drops; the warm air retains more moisture, leading to higher absolute humidity. East-facing rooms receive morning sunlight with relatively cooler temperatures. By the afternoon, as the sun moves, these rooms cool down. The cooler air contains less moisture, so even if the same amount of water vapor is present, the absolute humidity is lower in east-facing rooms compared to west-facing rooms.

The experiment SS: RBB, with no cross ventilation, allows moisture to become trapped inside the west-facing rooms, resulting in higher absolute humidity levels. The indoor AH remains consistent across all experimental seasons when compared to the fluctuating RH (%) outside, as seen in Table

52, 53, 54, and 55. The envelope system under passive conditions demonstrates its ability to maintain AH within a comfortable range during January's winter months and the transition months of March and April 2024. Table 54 shows that during the summer months of July and August 2023, indoor AH levels are high and would require active measures to reduce them to a comfortable range. In September, the east-facing living area has an AH level of 13-14 g/m³, which is very close to the comfortable range; however, the west-facing bedroom needs a reduction in AH levels.

Table 54: Context T(°C), RH(%) & AH(g / m3) across the winter & transitional seasons

t (Hrs.)	Winter			Transitional Season					
	Context (T) 17 & 18 Jan 24	Context (RH) 17 & 18 Jan 24	Context (AH) 17 & 18 Jan 24	Context (T) 13 & 14 March 24	Context (RH) 13 & 14 March 24	Context (AH) 13 & 14 March 24	Context (T) 04 & 05 April 24	Context (RH) 04 & 05 April 24	Context (AH) 04 & 05 April 24
6:00	20.8	77	**13.9**	17.9	69	**10.5**	20.7	59	**10.5**
12:00	29.9	32	**9.6**	31	25	**8.0**	32.7	19	**6.6**
18:00	25.1	44	**10.1**	28.2	45	**12.3**	33.2	27	**9.7**
0:00	22.8	50	**10.1**	23.3	72	**15.0**	24.3	66	**14.6**
6:00	18.8	62	**9.9**	20.3	77	**13.5**	19.4	78	**13.0**
12:00	28.6	38	**10.6**	32.3	18	**6.1**	33	21	**7.4**
18:00	25	50	**11.5**	30.1	38	**11.6**	32.2	34	**11.6**
0:00	20.6	63	**11.2**	24.3	73	**16.1**	24.1	63	**13.7**
6:00	18.6	72	**11.4**	21.4	75	**14.0**	19.6	64	**10.8**

RH helps in understanding potential condensation issues. Managing both RH and AH is essential for ventilation, temperature control, and the use of humidifiers or dehumidifiers to create a healthy and comfortable indoor environment.

Maintaining an indoor temperature range of 22-26 °C, with RH at 40-60%, and AH between 6-12 g/m³ is essential. Passive measures, such as cross ventilation, can lower indoor AH when outdoor AH is lower than indoor air, which is often possible during the cooler winter months in Dubai (November– March).

Table 55 demonstrates that in the summer, cross ventilation is adequate during the early morning and late evening hours when outdoor AH levels are lower. Using exhaust fans in moisture-prone areas, such as kitchens and bathrooms, can help remove excess moisture from the air. The strategic

use of active systems, such as humidifiers, dehumidifiers, and air conditioning, can maintain a comfortable indoor environment while promoting energy efficiency.

Table 55: Context T(°C), RH(%) & AH(g / m3) across the peak summer seasons

t (Hrs.)	Peak Summer								
	Context (T) 17 & 18 July 23	Context (RH) 17 & 18 July 23	Context (AH) 17 & 18 July 23	Context (T) 22 & 23 Aug 23	Context (RH) 22 & 23 Aug 23	Context (AH) 22 & 23 Aug 23	Context (T) 23 & 24 Sept 23	Context (RH) 23 & 24 Sept 23	Context (AH) 23 & 24 Sept 23
6:00	33.3	35	**12.6**	30.7	66	**20.8**	30.6	64	**20.0**
12:00	46.4	20	**13.9**	45.9	11	**7.5**	46.6	5	**3.5**
18:00	41.4	33	**18.0**	40.3	40	**20.7**	40.2	31	**16.0**
0:00	35.5	62	**25.1**	34.9	67	**26.3**	34.4	15	**5.7**
6:00	31.8	70	**23.4**	31.8	75	**25.0**	32.1	19	**3.4**
12:00	46.6	11	**7.7**	44.9	26	**16.9**	45.1	1	**0.6**
18:00	40.6	47	**24.7**	40.2	45	**23.2**	40	28	**14.3**
0:00	35.3	61	**24.5**	35.2	68	**27.2**	34.9	13	**5.1**
6:00	33	71	**25.3**	33.1	76	**27.2**	31.8	10	**3.3**

4.3.3 Summary for the performance of the envelope system at the BaityKool prototype

The experiments conducted under passive conditions with no occupancy at the BK living lab across the seasons demonstrate the envelope system's potential for reducing indoor air temperature without any action (Exp. Ref). It reveals that the peak summer months, July, August, and September 2023, have an indoor air temperature reduction potential of 14-19°C, even when outdoor temperatures reach up to 46°C.

The envelope system at BK demonstrates a consistency in indoor air temperature achieved due to the thermal inertia of the enabling to keep a very gradual indoor air temperature fluctuation under passive condition.

Under passive conditions without any action, the envelope system could manage to maintain a consistent indoor air temperature. During the summer season, the indoor air temperature ranged from 33°C to 37°C when the external temperature was at a range of 31°C to 47°C. During the Winter season, indoor air temperature ranged from 22°C to 27°C when the external temperature was at a range of 16°C to 32°C. During the Transitional season (March and April) indoor air temperature ranged from 25°C to 28°C when the external temperature was at a range of 17°C to 34°C.

4.4 Smart Passive operations by seasons

The Psychrometric chart simulation in Fig 84 for the weather data at BaityKool living lab location TSC, Dubai analyze the climate data at the BailyKool site location indicating the potential passive strategies. The results of experiments for the actions tested under passive condition across the seasons indicate the possible combinations to benefit energy saving potential maintaining thermal comfort as shown below:

Season in extreme warm climate	Months	Actions	Strategies
Summer	May, June, July, August, September	Solar Shading	Active
Winter	November, December, January	Day and Night Ventilation, Night Ventilation	Passive and Active
Transitional Season	February, March, April, October	Solar Shading, Night Ventilation, Combination of Solar Shading and Night Ventilation	Passive and Active

The summer with high temperatures ranging from 34 – 49.5°C, Refer Section 1.2.2, Table 2, Fig 84 shows the need for an Active strategy to maintain a thermal comfort condition indoors. The actions of the dynamic solar shading curtain help in reducing the energy demand for air conditioning by reducing the indoor air temperature as indicated in Section 4.2.1, Table 24.

The Winter months have the maximum potential for passive strategies with the action benefits of Natural Ventilation as indicated in Section 4.2.2, Table 31. The use of air conditioning to maintain the indoor thermal comfort condition can be limited to few hours during the afternoon when the exterior temperature is above the ASHRAE 55 indoor comfort range. This season can take advantage of the Diurnal temperature. According to the experiment results as in Fig. 104, 105, 109, 110 the passive strategy can work during the night and early morning hours when the external temperature is in the comfortable range.

The transitional season with the high temperature range would require the active and passive strategy with the use of solar shading and the combined action of Solar shading, Night Ventilation, and combination of solar shading and night ventilation. The experiment results in Section 4.2.3 clearly indicated the temperature reduction benefits in Table 38.

The use of the DISTECH Control as in Fig.79 (c), 80, the Smart Building Management system at BaityKool with the set temperature based on the occupant's comfort can have automated operations of the passive and active strategies with the operations of the actions activated based on the seasons and occupant comfort preference. This DISTECH system also monitors the energy performance of the house across the season. An energy balance annually can be achieved with the potential reduced energy demand for air conditioning using the passive and bioclimatic strategies.

4.5 Chapter Summary

The chapter 4 presents the results of experiments focused on thermal comfort using passive strategies at the BaityKool prototype, designed for an extremely hot climate. The experiments were conducted at the BK living lab during peak summer, winter, and transitional seasons. The results show that solar shading and natural ventilation can effectively lower indoor temperatures. The solar shading device RBB successfully blocks direct solar rays from double-glazed areas, reducing heat gain with an average temperature decrease of 8°C on hot sunny days and about 3-4°C on hot cloudy days during peak summer. The ETC and ITC can lower temperatures by 1-3°C because of their translucent materials. The ETC is more effective as its fixed on the external face of the window, enabling it to block the solar rays directly to the window glazing.

The results demonstrate up to 3-8°C reduction in indoor air temperature with RBB shading, directly supporting objective 1 and 2 by confirming the effectiveness of bioclimatic solar shading in extremely warm climates.

Objective	Section in Chapter 4	Evidence Summary
Solar Shading potential : Dynamic solar curtains: RBB,	4.2.1	RBB is the most effective in blocking direct solar rays fixed externally for the double-glazed areas and generates maximum shading benefits for reducing indoor air

ETC, ITC) for the summer months		temperature, Table 24, Table 38 and Table 39
	4.2.1 (iv)	T fluctuation at indoors in east and west oriented room within 1°C in 6 hours intervals with SS: RBB, Fig.92, 93, Appendix D

Experiments with natural cross-ventilation between east- and west-facing rooms maintained a steady indoor temperature of 25-27°C, even as outside temperatures ranged from 18 to 32°C. The day ventilation in January showed potential reduction in indoor air temperature by 5°C with cross-ventilation. With the rising external temperature in April to 34°C by afternoon from 20°C at 6 am no indoor air temperature reduction potential was observed. But a consistent level of indoor air temperature of 24-27°C. Combining natural ventilation with solar shading improved a 5-6°C reduction potential in indoor air temperature was achieved in March. The external temperature in March ranged from 18-36°C. The night ventilation could take benefit of diurnal temperature variation with lowering temperature at the night to 23°C the cross-ventilation improves the thermal comfort at indoor with the air movement. The indoor temperature rises by 1.5°C due to thermal inertial of the brick lining tiles of the wall system at interiors and the concrete floor at night slowly releases the stored heat during the day.

The results demonstrate up to 2-3°C reduction in indoor air temperature, directly supporting objective 1 and 2 by confirming the effectiveness of bioclimatic strategy of free cooling with natural ventilation

Objective	Section in Chapter 4	Evidence Summary
Natural Ventilation	4.2.2	Potential free cooling is achieved with DV+NV during the winter season and NV during the transitional season. Table 31
Day Ventilation + Night Ventilation (DV+NV)	4.2.2 (i)	Action suitable only for winter season with T range 18-28°C, T reduction potential of up to 2-3°C as in Table 32.

		Table 41 shows Indoor air temperature consistent at 23 to 25°C when external T range varies from 18 to 30°C, Refer Table 80, 81 Appendix E Indoor air T fluctuation of 0.5-1°C in 12 hours interval, Refer Fig. 106, 107
Night Ventilation (NV)	4.2.2 (ii)	This action effective in with T drop by 5°C in January and 2-3°C in April, Table 33 NV action caused T increase by 2-3°C in 12 hours at night followed by drop by 1-2°C by day, Table 82, 83, Appendix E, Fig. 109,110

The results of the combined action of solar shading with night ventilation demonstrate up to 2-6°C reduction potential in indoor air temperature, directly supporting objective 1 and 2 by confirming the effectiveness of the combined strategy of keep temperatures cool at night and SS works alongside during the day in prolonging the free cooling effect.

Objective	Section in Chapter 4	Evidence Summary
Solar Shading with Natural Ventilation	4.2.3 (i)	Action suitable during the transitional season with the combination of SS and NV with benefits of temperature reduction with action as shown in Table 38. Refer Appendix F, Table 85, 86. Refer Fig. 113,114 to see the consistent indoor air T of 25 to 27 °C when exterior T range from 18 and 32 °C.

The patio environment has a 2°C lowered temperature across the day and night when compared with the external temperature at the BaityKool Lab context. This is achieved due to the C- shaped architectural from and its orientation maintain shade at the patio across the day, the solar pergola

additionally shades the patio during the peak sunlight hours. Vegetation on the patio, an aquaponic wall, and rooftop features contributed to visual comfort and helped reduce nearby solar radiation. The BaityKool prototype's envelope system kept indoor temperatures stable, with just 2-3°C fluctuations while outside temperatures ranged from 16 to 51°C. The indoor air temperature under passive condition with no use of air-conditioning during the scenarios of experiments in January was at 20-22°C, RH at 51-52 %, March with 24-27°C, RH at 52-56%, April with 19-34°C, RH at 47-57%, July with 29-33°C, RH with 53-62%, August with 27-30°C, RH with 68-75%, September with 27-30°C, RH with 46-54%.

The patio demonstrates up to 2-3°C lowered T at all times when compared with external T, RH at 10-15% higher than external environment. The shaded patio felt cooler to the human body than the exteriors. This is directly supporting objective 3 by confirming the effectiveness of the bioclimatic strategy building orientation and shading of patio with architectural form and solar pergola and the vegetative system.

Objective	Section in Chapter 4	Evidence Summary
Patio (courtyard) design influences thermal comfort	4.2.4, 4.2.4 (i) and 4.2.4 (ii)	Patio shading benefits, Table 40, Fig 120, Refer the Patio shading benefits Table 41 and 42 .

The envelope system could have the potential temperature reduction of 10°C in the peak summer, 9°C in winter, and 5-7°C in transitional months under passive conditions. An indoor temperature difference of 18°C was recorded when the outside temperature reached 46°C in August. Humidity levels remained within comfortable ranges during winter and were similar during transitional seasons. Although summer months showed higher indoor humidity during testing, the RBB solar shading device reduced humidity by 2 g/m³, which could be further managed by energy-efficient active systems like optimized air conditioning with reduced operating hours to maintain indoor temperature and humidity within comfort standards. This supports the management of the building operations and actions based on the seasons and comfort requirements meeting objective 4.

Objective	Section in Chapter 4	Evidence Summary
The envelop system performance and management of building operations and actions based on seasons and comfort requirements.	4.3.1	Indoor air temperature benefit achieved by envelope system across the seasons under passive condition with no dynamic solar shading, Table 48, 49, and 50

The experimental analysis facilitates further discussion in the next chapter about the BaityKool living lab and includes conclusions regarding strategies and actions related to thermal comfort and optimal performance. Recommendations are offered for bioclimatic architecture suitable for extremely warm climates, combining architectural measures with both passive and active strategies to conserve energy.

The smart management of the building's operation with the actions and active and passive strategies based on seasons and comfort requirements would directly support the objective 4 with effectiveness of the improved thermal comfort and reduced energy demand for air conditioning. The experiment results of all the actions validates the potential of performance benefits of the Bioclimatic architecture for the extreme warm climate with the strategies as indicated in Section 4.4.

Quick summary of Chapter 4

The SS RBB is more effecting than ETC and ITC and shows potential indoor air temperature reduction 3 - 8°C during the peak summer season.

Fixing Solar Shading Curtain externally gives better results with the potential to block the direct solar radiation from warming the glass and transferring heat inside

Consistent indoor air temperature of 27-32 °C could be achieved under passive conditions at BK living lab when in the peak summers when the exteriors had a range of 30 -47°C (Refer Section 4.2.1 (v) Summary for Experimental analysis of Solar Shading indoor effects)

The Natural Ventilation shows indoor air temperature reduction potential up to 5°C with external temperature of 16-32°C. This could show better results with external temperature lower than 20°C in the Winter and Transitional season.

A consistent indoor air temperature observed with the range 19°C to 22°C in Winters when exteriors show 16 -32°C . There is opportunity for potential free cooling with DV and NV when the outside temperature drops below 23°C.

The indoor air temperature fluctuation with action natural ventilation was at an average of 0.5°C achieved due to the thermal inertia properties of the BK envelope system. (Refer Section 4.2.2 (iii) for the Summary for Experimental analysis of Natural Ventilation indoor effects)

A lower indoor temperature by 3-6°C in east- and west-facing rooms can be achieved during the transitional season through night ventilation and solar shading. The SS RBB shows greater effectiveness in maintaining the free cooling gained with NV.

The thermal mass of the envelope system at BK demonstrates regulation of indoor temperatures throughout the day by 2-3°C in 24 hours interval . (Refer 4.3.2 (iii) for the Summary for Experimental analysis of natural Night Ventilation and Solar Shading indoor effects)

The action of the solar shading pergola and the architectural form and its orientation could achieve drops in temperature by 3°C in winter and by 1-2°C during transitional months and peak summer when compared to the external environment. (Refer Section 4.2.4 (iii) for the Summary for Experimental analysis of Patio managing outdoor effects)

The RH (%) was at 10-15% higher at the Patio when compared to the external RH % across the winter, transitional, and summer seasons (Refer Table 43).

The envelope system of BK demonstrated an indoor air temperature reduction potential of 14-19°C during the peak summer season, with no actions of solar shading curtains and natural ventilation.

The Winter and transitional seasons could maintain an indoor air temperature ranging from 22°C to 28°C when the external temperature was between 16°C and 34°C. Summers under passive

condition the envelop system with no air conditioning and no occupancy could maintain 33°C to 37°C (Refer Session 4.3.3 for the Summary for the performance of the envelope system at the BaityKool prototype).

Chapter 5.
Discussion and General Conclusion

Chapter 5: Discussion and General Conclusion

Introduction

The research analyzes with the theoretical studies the Scientific questions testing the potential of Bioclimatic architecture for the extreme warm climate. Experiments performed at the BaityKool living lab test and validate the research question addressing the below mentioned questions and objectives based on the actions using active and passive strategies:

- How effective are passive strategies such as solar shading and natural ventilation in enhancing thermal comfort in very hot climates?
- In what ways can traditional architectural principles be integrated into modern high-performance buildings in the UAE?
- What role does the building envelope play in reducing energy consumption and maintaining indoor comfort across seasons?
- How can findings from experimental living labs inform future regulations and design standards for bioclimatic architecture in arid regions?

Objectives:

- To analyze and test the potential of bioclimatic design for buildings in Dubai's extreme warm climate, testing the BaityKool prototype designed with these strategies for thermal comfort, which include solar shading and night ventilation.
- Test the bioclimatic strategies on the BaityKool prototype to evaluate the thermal comfort provided by solar shading and night ventilation.
- To assess how patio (courtyard) design influences thermal comfort in residential buildings located in extremely warm climates by analyzing its impact on temperature regulation.
- Assess the significance of proper, smart management of the building's operation based on seasons and comfort requirements.
- To verify through field experiments and validate the real-time performance of the recommended strategies.

Chapter 5 presents the findings on the performance of the BaityKool prototype, designed for the extremely warm climate of Dubai, United Arab Emirates, during experiments analyzing the impacts of bioclimatic strategies. This prototype incorporates bioclimatic measures to address the challenges posed by this climate. The study demonstrates the effectiveness of solar shading and natural ventilation in improving thermal comfort under passive conditions. Experiments were conducted on the BaityKool prototype during peak summer, winter, and transitional seasons. These experiments compare the air temperature and relative humidity inside rooms facing east and west within the experimental zone at BaityKool with those outside. The data of the sensors are presented in the Chapter 3 (Section 3.5).

5.1 Performance of Passive Cooling Strategies for Thermal Comfort in Hot Climates

The experiments at the BaityKool living lab under passive conditions offer crucial insights into the effectiveness of bioclimatic strategies in an extremely warm climate. The study and its findings help identify the potential to reduce energy demand for cooling loads and maintain indoor thermal comfort.

5.1.1 Performance of Solar shading

The benefits of the solar shading curtain, as shown by the performance of the SS RBB, ETC, and ITC in lowering indoor air temperature at the BK living lab during the 48-hour experiments, are listed in Table 56.

Table 56: Benefits of the action dynamic Solar Shading curtain to reduce indoor air temperature °C of the BaityKool prototype during 48 hours of experiment.

Exp. Month / Season	Dynamic Solar Shading Curtain (SSC)			Reference Table for data analysis
	RBB	ETC	ITC	
July	6 -8°C	1 - 4°C	2 - 3°C	Table 24, 25, 26, 27, Table 70,71,72
August	3 -5°C	0.5 - 2°C	0 - 1°C	
September	2 -3°C	0.5 - 2°C	0 - 1°C	

The Solar Shading Curtain RBB is most effective during the 48 hours of peak summer in July. August and September offer lower benefits due to decreased solar radiation indoors, caused by induced cloud seeding aimed at bringing rain to help combat rising temperatures in Dubai. Additional advantages include reduced solar heat gain with solar shading curtains, which block intense sunlight and prevent it from entering indoor spaces. This results in lower energy demands

for cooling and improves thermal comfort through passive measures. Actions are taken in each experimental zone with rooms facing east and west as the sun moves across the sky. The results show that solar shading RBB is most effectively applied to east-facing openings in the morning as the sun rises, then to south-facing openings by noon, and west-facing ones in the afternoon. This approach to solar shading RBB is feasible daily for standalone houses on a plot or for multi-oriented apartments.

Table 57 compares outdoor and indoor air temperatures recorded during the experiment. The references, where no action was taken, and the indoor temperature at the BK living lab were controlled using the dynamic solar shading RBB. This shows that RBB and the envelope system can keep a relatively steady indoor air temperature throughout the experiment, with measurements taken at 6:00 a.m., noon, 6:00 p.m., and midnight.

The solar shading RBB during peak summer showed an indoor air temperature difference of 6-8°C in July compared to no shading (see Table 56). Table 70 in Appendix D indicates that in July, the indoor air temperature difference from outside at 12 noon was 17.6°C and 17.2°C on two days. Without SS: RBB, the difference was 9.9°C and 9.5°C. This shows the benefit of using Solar Shading RBB during peak summer when outside temp reached 47.6°C–48.0°C at noon.

Table 57 illustrates the benefits of SS: RBB, showing consistent indoor air temperatures under passive conditions without air conditioning. In July 2023, temperatures ranged from 29.9°C to 30.3°C, then to 29.6°C at 6, 12, and 18-hour intervals. There was a 0.38°C increase in indoor air temperature over 6 hours, followed by a 0.7°C decrease during the next 6-hour period at midnight. In August 2023, the range was 28.5°C to 29.9°C, then 29.2°C at the 6, 12, and 18-hour marks. The indoor air temperature rose by 1.4°C in 6 hours and then decreased by 0.6°C in the following 6-hour interval at midnight. In September 2023, the range was 29.9°C to 28.8°C, then 28.1°C within the same intervals. The temperature increased by 1.1°C over 6 hours and dropped by 0.7°C in the next 6-hour period at midnight.

The indoor temperature in July, August, and September shows a similar pattern, with air temperature rising and dropping at six-hour intervals, as observed using SS RBB as indicated in Table 57.

Table 57: Comparison of the external air temperature range at the BK living lab location and indoor air temperature range in °C at the exterior of the BaityKool living and indoors at the intervals 06, 12 & 18 hours

Exp. Month	Ext. Air T(°C) range	Ext. Air T(°C) at 6 Hrs. INT.	Exp. Ref T(°C) at 6 Hrs. INT. (12.00)	Indoor Air T (°C) with SS: RBB at 6 Hrs. INT. (12.00)	Ext. Air T(°C) at 12 Hrs. INT. (12.00)	Exp. Ref T(°C) with no action at 12 Hrs. INT. (12.00)	Indoor Air T (°C) with SS: RBBat 12 Hrs. INT. (18.00)	Ext. Air T(°C) at 18 Hrs. INT.	Exp. Ref T(°C) at 18 Hrs. INT. (0.00)	Indoor Air T(°C) with SS: RBB at 18 Hrs. INT. (0.00)
July	31°C - 47 °C	47.6	36.4	29.9	44.4	36.1	30.3	39.3	36.3	29.6
August	31°C - 46°C	51.1	27.3	28.5	41.4	28.9	29.9	36.9	29.4	29.2
Sept.	33°C - 45°C	46.6	31.4	29.9	40.2	30.6	28.8	34.4	30.2	28.1

Exp. Ref with no action shows a difference in air temperature (°C) between the Exp. SS RBB and Exp. Ref in the 6-12-18 hours intervals as 6.5 – 5.8 – 6.6 °C. This shows a very similar range in the difference in air temperature achieved with the action of SS RBB. The external temperature for the same time intervals ranged from 47.6 to 44.4 to 39.3 °C, and the indoor air temperature, with action SS RBB, is 29.9, 30.3, and 29.6 °C, respectively. This clearly indicated the efficiency of the solar shading curtain RBB in blocking solar radiation and maintaining a consistent indoor air temperature.

A similar pattern of benefits is observed in August and September, indicating the potential of using the dynamic solar shading curtain to achieve improved thermal comfort indoors with reduced air temperature under passive conditions. This reduced air temperature has an impact on energy demand for air conditioning. The action of dynamic solar shading could enable a reduction in the time required for the air conditioning system to maintain a comfortable indoor air temperature.

The BK envelope system can lower indoor temperatures by 14°C to 19°C during peak summer months without relying on SS RBB (see Table 68). During a 48-hour peak summer test, indoor air temperature stayed within 2-3°C variation, and 1.5-2°C in winter under passive, unoccupied

conditions. This temperature control is due to the high-performance envelope and Low-E glazing on BaityKool windows and doors.

5.1.2 Benefits of Natural Day and Night Ventilation

Table 58 shows Dubai's hot climate, marked by large daily temperature swings, especially between day and night. From January to April and November to December, the temperature difference ranges from 5.6°C to 15°C, based on data from Station DWC Al Maktoum I.A, Dubai, 2012-2024, as shown in Table 2 and Fig. 127. BaityKool's passive natural ventilation keeps indoor temperatures comfortable with minimal energy use. Tests such as night and 24-hour ventilation lowered indoor temperatures by up to 5°C during peak times and 1°C in colder months. In April, combining night ventilation with solar shading can cut temperatures by up to 2°C during peak hours and 1°C at other times (see Table 38).

Table 58: Envelope performance benefits across the experiment months, demonstrating air temperature range in °C at the exterior of the BaityKool prototype and indoors at 6, 12 & 18 hours

Exp. Month	Ext. Air Temperature °C range	Indoor Air Temperature °C at 6 Hrs. interval	Indoor Air Temperature °C at 12-hour. interval	Indoor Air Temperature °C at 18 Hrs. interval
January	16°C - 32°C	23.1 °C	22.9 °C	26.5 °C
March	20°C - 34°C	26.1 °C	26.0 °C	25.9 °C
April	18°C - 36°C	26.9 °C	26.84°C	26.5 °C

With the fluctuating 16°C to 32°C exterior air temperature in January, the cross-ventilation experiment, involving both day and night, kept indoor temperatures steady at 23°C-25°C over 48 hours with the potential indoor air temperature reduction as shown in Table 59. It used cross ventilation between the west bedroom and east living room and kitchen, linked to patio ventilation in the corridor (see Tables 79 and 80). Without cross-ventilation, indoor temperatures rose from 23°C to 26.4°C. With it, a consistent 24°C was maintained despite external temps reaching 29.9°C and 28.6°C at noon on days 1 and 2. When outside dropped from 29.9°C to 18.8°C, indoor temperatures stayed at 24°C. This was due to floor and wall thermal mass absorbing and slowly releasing heat. Cross ventilation also facilitated nocturnal cooling by dissipating heat through cool night air.

Opening the window at 15 degrees didn't affect indoor temperature despite rising outdoor temps. External wind enhances comfort through skin cooling. While indoor temperature impact is minimal, air flow increases comfort. Managing opening size is important due to dust from seasonal sandstorms. The controlled window and translucent curtain filter dust, let air in, and reduce indoor dust, ensuring cleaner, healthier indoor air.

The January night ventilation experiment showed a potential 5°C reduction in indoor air temperature. External temperatures varied from 15.6°C at 6 hours to 28.7°C at noon, then 18.4°C at 24 hours. Indoor temperature stayed steady at 20-21°C over 24 hours, with a 1.5-2°C increase at night as outside temperatures dropped from 25.3°C. At noon, indoor temperature fell 2°C due to the BaityKool Envelope's thermal mass. (See Tables 82, 83, 84 for data and benefits of night ventilation.)

Night ventilation reduces indoor temperature by replacing hot air with cooler outdoor air, improving thermal comfort. The BaityKool prototype's window placement and adjustable size optimize airflow aligned with prevailing winds. Night ventilation didn't change indoor relative humidity, maintaining around 47% RH in the east room and 54-56% in the west, despite outdoor humidity varying from 39% to 67% over 18 hours.

Table 59:Indoor air temperature benefits with action Natural Ventilation: DV+NV, NV at the East and West oriented room of the BK living lab in the Winter months.

Exp. Month / Season	**Natural Ventilation**				**Reference Table for data analysis**
	Exp. DV + NV		**Exp. NV**		Table 79 to 84 Appendix E
	East Oriented Room	**West Oriented Room**	**East Oriented Room**	**West Oriented Room**	
January	2°C	3°C	3°C	3°C	

The April night ventilation experiment in a transitional season didn't significantly reduce indoor air temperature (see Table 83) because the minimum external temperature stayed above 15°C at night, rising to 33°C by noon.

The natural night ventilation strategy performs effectively when there are substantial daily temperature fluctuations, the outside temperature is below 15°C, and a consistent breeze improves cross ventilation.

5.1.3 Benefits of Combined Natural Ventilation and Solar Shading

March experiments tested natural night ventilation with solar shading, using Roller Blind Blackout and External Translucent Curtain, to evaluate their effectiveness in reducing daytime heat and maintaining coolness at night. The combined approach uses solar shading to block heat during the day and nighttime ventilation to expel indoor heat, leveraging diurnal temperature changes. As temperatures fall at night, cross ventilation cools the building via its thermal mass, resetting indoor temperatures for the next day. This method accelerates passive cooling, with solar shading stopping heat entry and thermal mass releasing stored heat during the night. The March results as in Table 60 indicate that this combination effectively cools the building, acts as a heat sink, delays indoor temperature peaks, and significantly reduces energy consumption.

Using natural night ventilation with RBB solar shading, the indoor temperature dropped 6°C at noon during a 6-hour experiment with outside temperatures of 35 °C and indoor 24°C. Over 24 hours, indoor temperature decreased only 1 °C as outside temp stayed at 24°C. On day two, similar results occurred with a 6 °C drop during a 30-hour experiment with outside temperatures of 36 °C and indoor 25 °C. Combining measures shows solar shading's daytime impact in reducing and stabilizing indoor temperatures, with less fluctuation. Relying on solar shading alone in transitional seasons misses the benefits of free night cooling, which uses natural temperature cycles to boost indoor comfort.

With the night temperature at the exterior ranging from 20°C to 24°C, there was limited benefit in reducing the indoor air temperature with natural cross ventilation. The advantage of reducing indoor air temperature was achieved with the RBB solar shading; however, the ETC curtain was also ineffective in reducing the temperature by more than 1°C.

The thermal mass cooling was observed as the interior clay-lined walls and concrete flooring discharged the stored heat of the day during the night with night ventilation. The night ventilation helps keep the indoors fresher the next day. Cross ventilation enables faster heat dissipation when the exterior temperature is below 15°C.

Table 60: Natural Ventilation benefits with reduced air temperature °C for the indoors of east and west-oriented rooms of the BaityKool living lab.

Exp. Month / Season	**Natural Ventilation and Solar Shading**		**Reference Table for data analysis**
	Exp. NV+SS: RBB		Table 38, 39,85, 86
	East Oriented Room	**West Oriented Room**	
March	3°C	3°C	

Passive natural night ventilation with solar shading enhances indoor thermal comfort and reduces energy consumption for cooling. It also decreases the need for mechanical ventilation during the day.

The analysis of results with passive natural ventilation, as shown in Table 31, indicates that it can reduce indoor air temperature by 5°C at noon, thereby enhancing comfort without the need for air conditioning.

5.2 Influence of Patio Design on Microclimate and Indoor Comfort

The patio design is an essential incorporation in the design of buildings in hot climates, as seen with its benefits in traditional architecture, incorporating solar shading, natural ventilation, and evaporative cooling. BaityKool's bioclimatic approach takes inspiration from courtyard medinas, featuring a north-facing, breeze-cooled patio and a C-shaped layout for shade. Aquaponics research was conducted alongside the patio experiment and may have influenced its temperature.

Section 4.2.4 (i) Table 40 shows that indoor air temperature at the patio drops by 2 °C during Peak Summer, winter, and transitional seasons, thanks to shading and a dynamic solar pergola with BIPV panels. Fig. 120 highlights the BaityKool prototype's orientation to the Sun, using an introverted design with double-glazed facades facing the courtyard and vegetated, shaded facades for controlled indoor conditions. Cross-ventilation from an aquaponics wall and patio ventilator, along with vegetation and irrigation, enhances cooling. During experiments, a consistent 2°C reduction was observed at the patio during the day in January, July, August, September, and a 3°C decrease in March and April; at night, the reduction was 2°C in several months and 3°C in April. The pergola shades the patio from 9 am to 4 pm, reducing temperature and increasing comfort (see Section 4.2.4, Tables 41, 42, 46 59, 60, 64).

Relative humidity (RH) is 10-15% higher during experiments compared to outside. At 12 noon, RH is 40-50% in winter, 25-35% in transitional, and 15-30% in summer when outside is hot. By 6 pm, RH rises to 50-60% winter, 40-55% transitional, and 40-60% in summer. RH at the patio remains higher than outside due to surface cooling, vegetation, and localized condensation, creating a self-moisturizing microclimate.

5.3 Integration of Vernacular and Bioclimatic Principles in Modern Architecture

Fig. 84's Psychrometric graph displays Dubai's BaityKool data, confirming the design for warm climates. It links climate, building design, comfort, and system controls. December-February fall within the comfort zone. November-March can utilize passive ‘Natural ventilation’. November-April can implement Mass-Cooling. October-May can combine ‘Mass-Cooling and Night Ventilation’. June-September require ‘Air-conditioning and Dehumidification’.

The BaityKool design uses passive strategies for better thermal regulation: adjustable solar shading, building orientation, passive ventilation, and high thermal mass. Night ventilation cools the thermal mass, making the building climate-responsive and reducing energy use. The design features a compact envelope with UHPC walls that protect against sunlight and a terracotta lining that regulates humidity. Its U-shaped form with a north-facing courtyard uses nighttime winds effectively. Walls insulate sound and temperature, while the building's mass shades exterior walls. A movable solar pergola covers the courtyard during the day and retracts at night for airflow and heat removal. The stepped roof, vegetation, irrigation, water features, and aquaponics system enhance thermal comfort through natural cooling and shading, thereby lowering summer temperatures.

The action of limiting the external-facing windows to two elevations facing east and west. Keeping the glazed window area within 20% of the surface area and shading the glazing with perforated UHPC panels helped minimize the solar heat gain. The placement of the windows, along with their opening direction, allowed for flexible modular plans that enhanced cross ventilation and thermal performance indoors. The use of clay bricks in the interior boxes, integrated into the CLT wood in the wall composition, has improved insulation and hygrometric regulation to maximize thermal comfort.

The use of materials with high thermal mass, such as wood, clay bricks, and concrete, on walls and floors can absorb heat during the day and slowly release it at night. This process delays heat penetration, reduces heat transfer, and stabilizes indoor air temperature fluctuations. Nighttime passive cooling leverages daily temperature fluctuations, thereby decreasing dependence on air conditioning and reducing energy consumption. Incorporating bioclimatic strategies, along with passive and semi-passive solutions and high thermal inertia materials, greatly enhances thermal comfort and energy efficiency. Additionally, utilizing sustainable, biodegradable, reusable, and recyclable bio-based materials helps decrease pollution and toxic emissions from synthetic materials, ultimately reducing the carbon footprint.

BaityKool's innovative systems, [22] include , ‘Radiative Sky Cooling’ [91], ‘Building integrated Photovoltaics’, ‘Aquaponics module’ [92], ‘Lumbrifilter’ biological water treatment , and ‘Solar cover over the patio with the vegetation. Its automation system, using intelligent building and water management, enhances performance with real-time monitoring and control based on occupant comfort.

BaityKool uses the ‘Cool Degree Days’ method [73], including techniques such as ‘External heat protection’, ‘Interior heat reduction’, ‘Heat evacuation’, ‘Cold production’, and ‘Heat adaptation’. In summer and transitional seasons, it employs ‘Night heat evacuation’ and ‘Thermal mass storage’ during winter and transitional seasons [62]

The BaityKool experiments, designed for a hot climate, assess the benefits of year-round indoor thermal comfort. The innovative envelope systems with the action of dynamic solar shading curtain, natural ventilation, combination of natural ventilation with solar shading, patio based design with solar shading, the test performed under passive and semi-passive strategies enhance comfort and cut energy use for air conditioning, maintaining an annual energy balance.

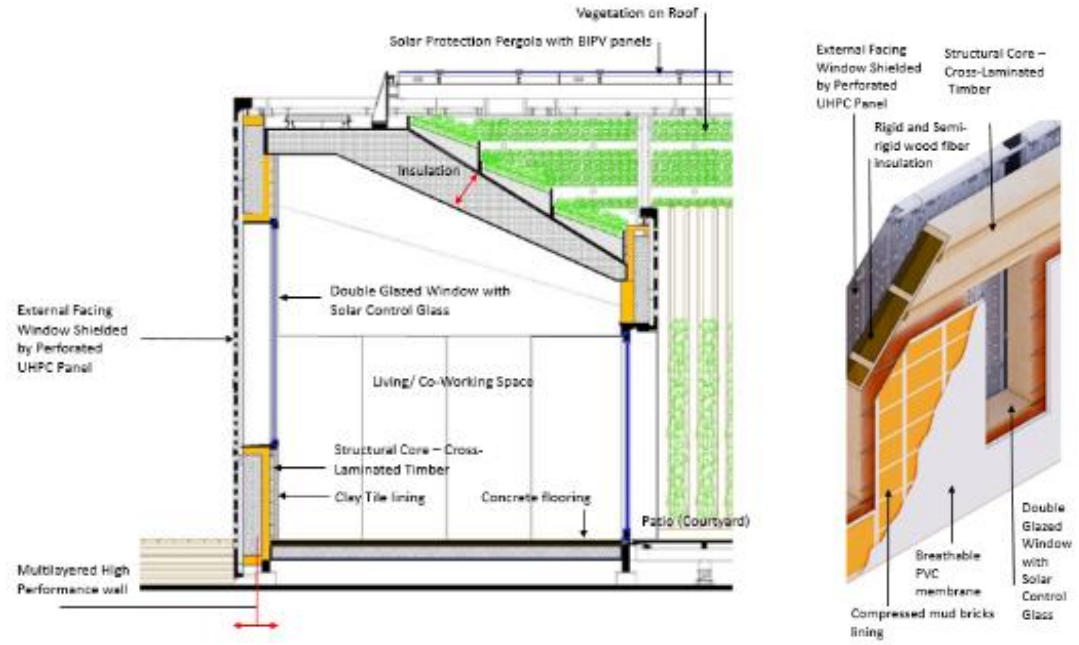
5.4 Performance of the Building Envelope for Thermal Stability and Energy Reduction

The solar shading system at BaityKool, featuring perforated UHPC panels on the exterior-facing windows, effectively blocks direct sunlight on the glazing. There is a reduction in indoor solar heat gain. The exterior air temperature ranges in °C, along with the potential for lowering indoor air temperature in °C during the experiment months based on a 6-hour benefit period (12 noon) and 12 hours (18 PM) is shown in the table 61, with reference table numbers indicating the respective months.

Table 61 indicates the reduction potential in indoor air temperature across the experiment months and seasons. There is a higher effectiveness in reducing indoor air temperature by 10–15 °C during the peak summer months at 12 noon for a 6-hour experiment duration. The benefits decrease by 5 °C at 18 hours in the evening due to the heat gain caused by partial sunlight entering the indoors through the glazing and generating radiant heat.

Table 61: Temperature °C in exterior across the experiment months and air temperature °C reduction potential at indoors of BaityKool prototype with the perforated UHPC façade design as a passive solar shading screen for external facing windows.

Exp. Month / Season	**Ext. Air Temperature °C range during experiment period**	**Indoor Air Temperature °C reduction potential with perforated UHPC panel at 12 Hrs. (6 Hrs. interval)**	**Indoor Air Temperature reduction potential °C with perforated UHPC panel at 18 Hrs (12 Hrs. interval)**	**Reference Table for data analysis**
January (Winter)	16°C - 32°C	9°C	5°C	Appendix E, Table 79 to 82
March (Transitional Season)	20°C - 34°C	7°C	6°C	Appendix F, Table 85 and 86
April (Transitional Season)	18°C - 36°C	5°C	2°C	Appendix E, Table 83
July (Peak Summer)	31°C - 47 °C	10°C	5°C	Appendix D, Table 70
August (Peak Summer)	31°C - 46°C	15°C	11°C	Appendix D, Table 71
September (Peak Summer)	33°C - 45°C	14°C	9°C	Appendix D, 72



(a) **(b)**

Figure 123: (a) Sectional elevation through the high-performance multilayered envelope system of BaityKool at the living room-oriented East. (b) Sectional view of the high-performance multilayered wall system showing the layers of materials from exterior to interior.

The high-performance wall, featuring a perforated UHPC panel, as shown in Fig. 123, effectively serves as a solar shading element. Its perforations block intense and low-angle sun rays, reducing heat, glare, and radiant heat gain indoors, thus enhancing thermal comfort. The BaityKool prototype's dynamic solar shading improves shading effectiveness. It maintained indoor air temperature within 1°C to 2°C during 12 hours of sunshine from 6 to 18 hours.

Indoor Relative humidity (RH) stayed stable throughout the experiment. Table 62 compares indoor RH with exterior fluctuations. The envelope system-maintained RH with gradual changes. Stable indoor temperature prevented RH swings. Wall and floor materials' thermal inertia absorbed heat during the day and released it at night, avoiding rapid temperature shifts. This kept indoor RH consistent without air conditioning.

Table 62: Envelope performance benefits across the experiment months, demonstrating the Relative Humidity range in (%) at the exterior of the BaityKool prototype and indoors at 6, 12 & 18 hours

Exp. Month	Ext. Relative Humidity (%) range	Indoor Relative Humidity (%) at 6 Hrs. interval	Indoor Relative Humidity (%) at 12 Hrs. intervals	Indoor Relative Humidity (%) at 18 Hrs. interval
January	32% -77 %	51%	52%	52%
March	25% - 77%	57%	57%	55%
April	19% - 78%	49%	51%	52%
July	20% - 71%	56%	56%	58%
August	11% - 76%	68%	75%	73%
September	05% - 64%	56%	55%	54%

The high-performance multilayered wall system features UHPC panel perforations that act as a fixed solar shading device. This blocks direct sunlight while allowing diffused light, reducing the solar heat gain indoors. The high-performance concrete acts as a hard-core protection from the sandstorm. The air gap between the UHPC panel and the vapor barrier allows heat to diffuse through the pores, preventing the trapping of heat within the wall layer. The solid and semi-solid wood fiber insulation with the external vapor barrier lining plays a critical role in maintaining thermal comfort indoors with thermal regulation, moisture control, and air tightness. The wood fiber, with its low thermal conductivity, provides better thermal resistance through high thermal lag and is also a sustainable material, being biodegradable and carbon-negative. The semi-solid wood fibers and clay tile ling made from raw earth add thermal inertia, delaying heat transfer. The aluminum-foiled vapor barrier reflects solar radiation, blocks moisture ingress, and prevents the risk of condensation in the insulation layers.

Cross-Laminated Timber (CLT) provides strong structural qualities, high thermal mass, and natural insulation properties. It absorbs heat during the day and releases it at night, helping to lower indoor peak temperatures. It also aids in moisture regulation through hygroscopic buffering, as the wood fibers absorb and stabilize excess indoor humidity. The interior-lined compressed mud bricks work together with the CLT to control humidity; clay absorbs excess moisture and releases

it when the air is drier, maintaining a consistent indoor relative humidity despite outdoor fluctuations [51]. Additionally, these bricks improve thermal storage, reducing temperature swings.

The breathable PVC acoustic canvas is the innermost layer, enhancing insulation and airflow. It prevents moisture buildup, works with the mud brick tile lining to regulate humidity, and reduces air and structure-borne noise.

The metal-decked concrete floor of the BaityKool Prototype increases thermal mass by absorbing heat from solar gain, occupants, appliances, and warm air, delaying peak indoor temperature by 6–8 hours. It stores heat without quickly raising indoor air temperature, gradually releasing it as outdoor temperatures drop, reducing daytime cooling needs. During natural ventilation, stored heat resets thermal capacity for the next day. In Dubai's climate with large temperature swings, this lag prevents indoor temperatures from matching outdoor temperature peaks.

The BaityKool Prototype's roof features radiative sky panels, a solar water heater, stepped planters with vegetation and an irrigation system, an Ultra-ply TPO membrane as a weather barrier, and reflective surfaces that reduce solar heat gain to keep interiors cool. Its structural plates are made of bi-sourced materials filled with recycled newspaper cellulose wadding, reducing heat and improving thermal comfort. Vegetation in the planters affects indoor temperature through evapotranspiration, releasing moisture that cools the air. The soil layer also insulates and adds thermal mass, blocking direct sunlight.

The prototype's door and window double glazing uses solar control glass to reject heat and admit daylight. The low-emissivity coating and double glazing reduce solar heat gain, providing insulation. BaityKool's envelope system maintained stable indoor temperatures during experiments, with delayed heat transfer and moisture control.

5.5 Limitations and Challenges in the Research

Changing climate and summer weather in the UAE caused induced rain to combat heat, leading to cloudy days and weather shifts. Experiments were repeated at different times to establish a baseline and test, with similar temperature and humidity ranges for comparative analysis.

The prototype's air-tightness was low at 20 volumes/hour at 50 bars in the corridor, mainly due to issues with the aquaponics wall's joinery between the wood veneer and fish tank. Gaps were sealed to improve air tightness, impacting corridor indoor temperature.

The direct access to the Patio from the Living and Bedroom using the large sliding folding door lacked a buffer during the peak summer, with loss of conditioned air when the doors were ever opened.

The experiments and tests performed at the aquaponics system at the BK living lab and the sparse vegetative not covering the complete roof during the experiment duration had an influence on the patio air temperature.

5.6 General Conclusions

The experiments at the BaityKool prototype on bioclimatic architecture, designed for extremely warm climates, demonstrated significant potential to reduce indoor air temperature, improve indoor thermal comfort, and lower energy use for mechanical cooling through passive and semi-active strategies.

Using dynamic solar shading with curtains is very effective during peak summer months. SS RBB effectively blocks direct sunlight from double-glazed areas, reducing heat gain with an average temperature drop of 8°C on hot, sunny days and about 3-4°C on hot, cloudy days.

Dynamic solar shading curtains on exterior openings effectively lower indoor air temperatures by blocking solar radiation before it reaches the glazing. The fixed exterior curtain outperforms internal translucent curtains by reducing heat gain, with SS RBB acting as a shield by absorbing and reflecting heat outward. Deployed during peak sun hours following the sun's path, they are essential in hot climates.

Natural ventilation utilizes climate patterns in hot areas, allowing for nighttime ventilation in December and January. Combining direct and natural ventilation reduces indoor temperatures by 3-5 °C. Rooms with openable windows facing the wind see larger drops and better comfort as cooler outdoor air enters through drafts.

In very warm climates, DV + NV cooling is most effective in winter when outside temperatures fall below 20°C to 23.5°C, according to ASHRAE 55 indoor thermal comfort standards. It's especially efficient with large temperature differences between day and night. In January, indoor temperatures were lowered by 2-3°C, while outside temperatures ranged from 16°C at 6 am to 32°C at noon. Buildings in these climates can use this passive method to cut down on air conditioning energy use during the winter.

Natural night ventilation effectively lowers indoor temperatures during winter and transitional seasons, with actions performed a few hours after sunset and before sunrise. Greater benefits in reducing indoor air temperature are achieved when the climate has a high diurnal temperature range. At night, stored heat from roof and wall insulation is released, while cooler outdoor air lowers indoor temperatures by 2-5°C in winter and 1-3°C during transitional seasons. Proper envelope design and material choice enhance these effects. Ventilation causes temperatures to slightly rise at night and gradually fall during the day by replacing warm indoor air with cooler outdoor air. Cross-ventilation through correctly oriented and sized windows improves thermal comfort by maximizing airflow. Natural night ventilation does not influence indoor relative humidity variation. A consistent level of relative humidity (RH%) is maintained in both east- and west-oriented rooms with natural ventilation.

Solar shading and natural ventilation reduce temperatures by 1-5°C in October, November, March, and April, keeping indoor temperatures cooler both day and night. The envelope system, which includes a clay lining, tile cladding, and a concrete floor, helps control indoor temperatures, thereby lowering the need for air conditioning during transitional seasons.

The patio design creates a microclimate that reduces patio temperatures by 3°C at noon in winter and 1-2°C during transitional months and summer compared to outside. The shaded courtyard and solar pergola help keep interior walls cool. At night, the courtyard radiates heat into the sky, and the patio walls and floor release stored heat, producing a cooling effect. Vegetation on the patio, roof, and green wall of the aquaponics system forms a habitat that also helps keep air temperatures 2-3°C lower than outside, both day and night.

The patio microclimate influences indoor comfort through natural ventilation from November to March. The vegetative roof and trees provide shade for the building, enhancing the thermal

environment. The design focuses on the courtyard with large inward-facing openings. Its self-shading shape helps keep patio-facing rooms cooler by reducing heat gain. A dynamic solar pergola offers additional shade for the patio. Using a wall layer at the exterior with high thermal mass materials allows the walls to absorb heat from the intense sun and hot air. This wall layer prevents immediate heat radiation into the courtyard and surrounding areas during the day. The shaded patio walls reduce solar radiation, as their surface temperature remains closer to ambient air temperature. The shaded thermal mass absorbs excess heat from the courtyard, improving thermal comfort. At night, as the outside temperature drops, the stored heat is released. The warmer walls radiate heat out to the cooler courtyard and night sky. The dynamic solar pergola at the patio provides shade during the day and, when open at night with cross ventilation, helps release heat from the courtyard.

The key consideration is to have the walls facing the patio with a thermal mass layer on the exterior face. Having the courtyard-facing walls with perforations and an air gap between the inner insulated layer helps to evacuate heat through stack ventilation. The air gap acts as insulation because the heated air becomes less dense and rises along the wall layer, which has open gaps at the top and edges, allowing cool air to be pulled from the bottom of the courtyard. This creates a passive upward airflow within the gap. Additionally, shading the patio-facing walls' mass from direct sunlight is important to prevent heat overload in the wall, which cannot dissipate heat in a single night. Integrating vegetation further improves thermal comfort in the patio through evapotranspiration and cross ventilation. Strategically placing vegetation and water bodies in the patio can channel cool breezes into the space, enhancing the synergy of architecture and nature for climate control with bioclimatic design. The combination of a shaded patio and ventilated courtyard creates a microclimate around the patio, characterized by lower air temperatures compared to the outside, helping to stabilize indoor air temperature.

The envelope system design is essential in hot climates because it acts as a solar and thermal barrier, reducing heat transfer. The BK envelope system, in passive, unoccupied conditions, proved to be an effective obstacle throughout the year. During peak summer, it lowered indoor temperatures by 14-19°C, even when outdoor temperatures reached 48°C, without the use of solar curtains. Its thermal inertia helps maintain steady indoor temperatures, minimizing fluctuations

with slow increases and decreases, reducing temperature peaks and balancing temperature differences between day and night.

During summer, passive strategies such as high-performance envelope systems with high thermal mass materials, solar shading, airtightness, low-emissivity glazing, and night ventilation effectively remove heat when nighttime temperatures are cooler. Active systems benefit from solar shading but still require mechanical cooling to maintain a comfortable environment.

During winter, passive strategies like the thermal envelope system used in summer store heat during the day and release it at night. Air tightness and insulation stabilize indoor temperatures with minimal fluctuations. Natural ventilation can be improved with an external translucent curtain to filter dust. Active systems like mechanical cooling can be minimized to maintain thermal comfort. Fans enhance natural ventilation sensations and extend comfort.

In the transitional season, the passive strategies include natural night ventilation, a combination of solar shading with night ventilation. The active systems are required to maintain thermal comfort indoors during the day. The use of mechanical cooling can be reduced with use of passive strategies and the use of fans can improve the thermal comfort range.

In the extreme warm climate, indoor thermal comfort requires both passive and active strategies. Passive methods initially lower energy use, reducing dependence on mechanical cooling. Active systems then efficiently meet comfort needs, with passive actions further decreasing reliance on mechanical cooling and enhancing resilience. The envelope system should have a high-performance, eco-friendly design that reduces heat transfer, manages energy, and cuts cooling needs. Smart building systems enable dynamic control of shading, windows, and ventilation, balancing mechanical cooling with passive strategies for thermal comfort based on occupant conditions. Bioclimatic design, using shading, natural ventilation, and integrated measures, conserves cooling energy through active and passive methods.

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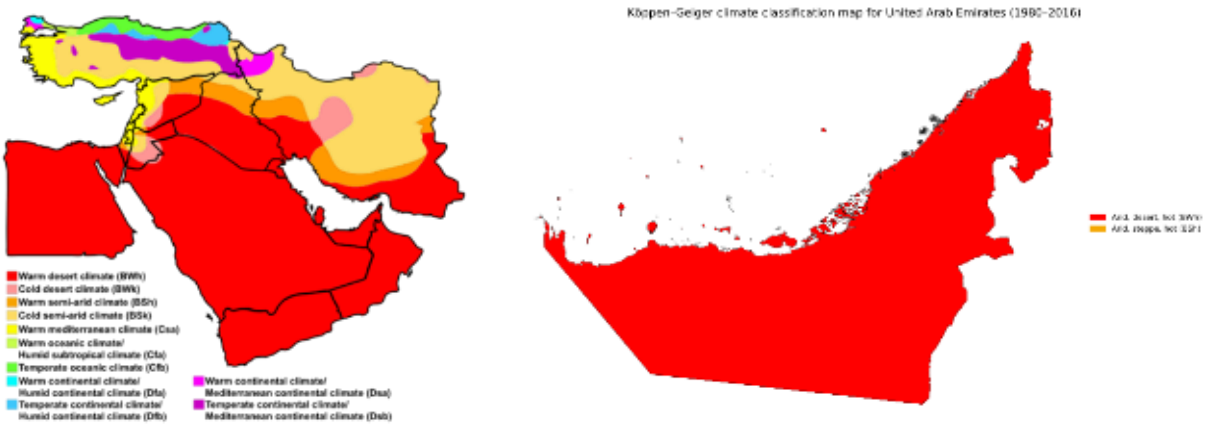
Appendix

The Climate Conditions at Dubai, UAE

The climate across the seven emirates in the UAE is generally the same, with variations based on the microclimatic conditions of the location, weather its coastal or the desert.



(a) (b)

Figure 124: (a) Middle East map of Köppen climate classification, Image: (b) Köppen climate classification map, UAE (Source: http://hanschen.org/koppen)

Meteorological data spanning 2012-2024 for Al Maktoum International Airport's (DWC) weather station, Longitude: 55 10 32 E, Latitude: 24 55 06 N, Elevation: 52 m, analyzed for Temperature, Relative Humidity, Wind speed, Rainfall & Solar Radiation. The figure 120 shows the map of UAE with the location of the weather station DWC.



Figure 125: Climate Station Locations, Al Maktoum International Airport's (DWC) weather station, Dubai, UAE

a) **Temperature – T (°C):**

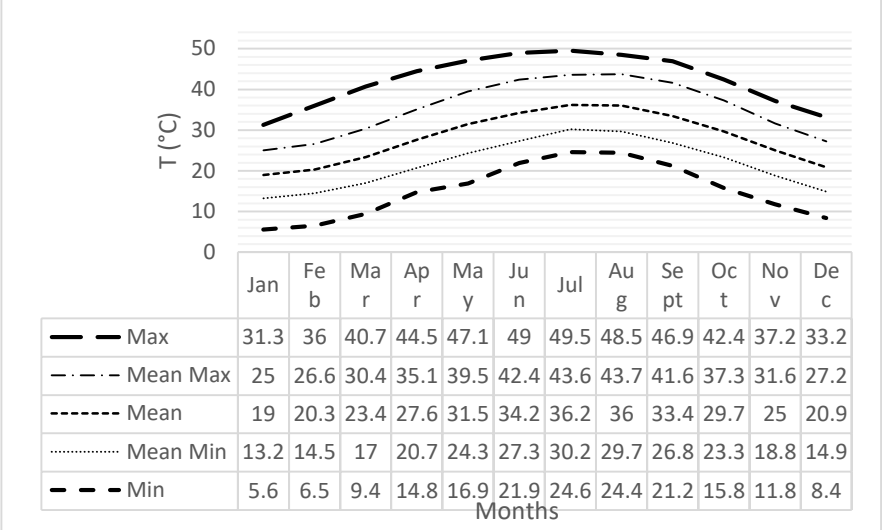
The air temperature measures the thermal energy of the ambient air expressed in °C, a primary climatic parameter influencing Human thermal comfort, building material performance, and passive design strategies. The graph in Fig. shows T measured under the standard condition of a shaded and ventilated enclosure at 1.5m above ground.

- Maximum T °C (T Max) refers to the highest recorded air temperature during a specific time (typically 24 hours); this information guides the design of the shading system and the calculation of the cooling load.
- Mean Maximum Temperature (Tmean_max) represents the arithmetic average of daily maximum T recorded over a specific period, which guides the passive cooling system design.
- Mean Temperature (Tmean) is the average of T measurements over a specific period; this determines the passive design strategies, the heating/ cooling degree days, and the insulation requirements for the envelope system.

  Tmean = (Tmax + Tmin) / 2

  where Tmax = daily maximum T, Tmin = daily minimum T.
- Minimum Temperature (Tmin) represents the lowest recorded air temperature during the 24-hour period before sunrise. This temperature guides the passive survivability thresholds and influences the building envelope system specification.
- Mean minimum temperature (Tmean_min) is the average of the lowest daily T recorded over a period of time; this represents the nighttime cooling potential.

Dubai has a hot climate during most months of the year, with the summer extending from May to October, with the temperature ranging from 28 to 36 °C and reaching 48 °C in the months of July and August. Winter season extends from November to April, with the mean temperature ranging from 19 to 27 °C. January and February have the coolest temperatures, falling to 18 °C. The south side of the emirates requires shading devices in buildings to block solar heat gain compared to the north, which is a comfortable zone due to the lack of direct solar radiation [41].



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Max	31.3	36	40.7	44.5	47.1	49	49.5	48.5	46.9	42.4	37.2	33.2
Mean Max	25	26.6	30.4	35.1	39.5	42.4	43.6	43.7	41.6	37.3	31.6	27.2
Mean	19	20.3	23.4	27.6	31.5	34.2	36.2	36	33.4	29.7	25	20.9
Mean Min	13.2	14.5	17	20.7	24.3	27.3	30.2	29.7	26.8	23.3	18.8	14.9
Min	5.6	6.5	9.4	14.8	16.9	21.9	24.6	24.4	21.2	15.8	11.8	8.4

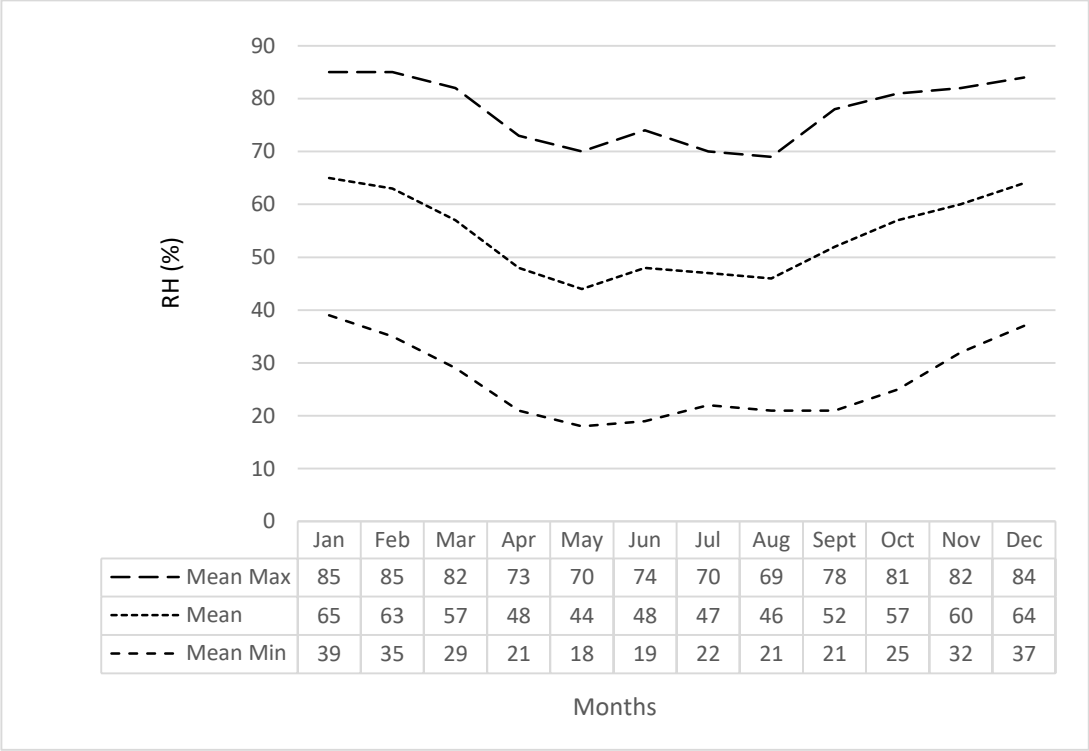
Figure 126: Air Temperature (°C) graph for Dubai, Al Maktoum International Airport's (DWC) weather station for 2012 -2024 (Source: https://www.ncm.gov.ae/services/climate-reports-yearly)

b) **Relative Humidity - RH (%):**

Humidity is the measure of water vapor in the air surrounding us; the more moisture, the higher the humidity. The relative humidity indicated in percentage shows the maximum rate of water vapor the air could hold, depending on the temperature. Dubai, being in proximity to the Arabian Gulf, has coastal areas that are more susceptible to humidity in comparison to the inland areas of Al Ain and the mountainous region in the Northern Emirates, which have humidity arising from water bodies. The rise in temperature leads to an increase in the moisture caused by the evaporation of the sea into the atmosphere. The graph in Figure 1.5 shows RH (%) measured under the standard condition of the shaded and ventilated enclosure at 1.5m above ground.

- Mean Max RH (RH mean max) represents the average of the highest daily humidity values recorded over a specific period; this influences the evaporative cooling potential, determines condensation risk, and guides ventilation requirements.
- Mean RH (RH mean) is the average RH value over a specified period of time; it represents the moisture content in the air relative to its maximum capacity at a given T; this guides the moisture management strategy and influences the material hygrothermal performance.
- Mean min RH (RH mean min) represents the average of the lowest daily relative humidity values recorded over a specific period. It indicates the driest atmospheric conditions for a

location; this determines peak evaporation potential, guides the passive cooling system design.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Mean Max	85	85	82	73	70	74	70	69	78	81	82	84
Mean	65	63	57	48	44	48	47	46	52	57	60	64
Mean Min	39	35	29	21	18	19	22	21	21	25	32	37

Figure 127: Relative Humidity graph for graph for Dubai, Al Maktoum International Airport's (DWC) weather station for 2012 -2024 (Source: https://www.ncm.gov.ae/services/climate-reports-yearly)

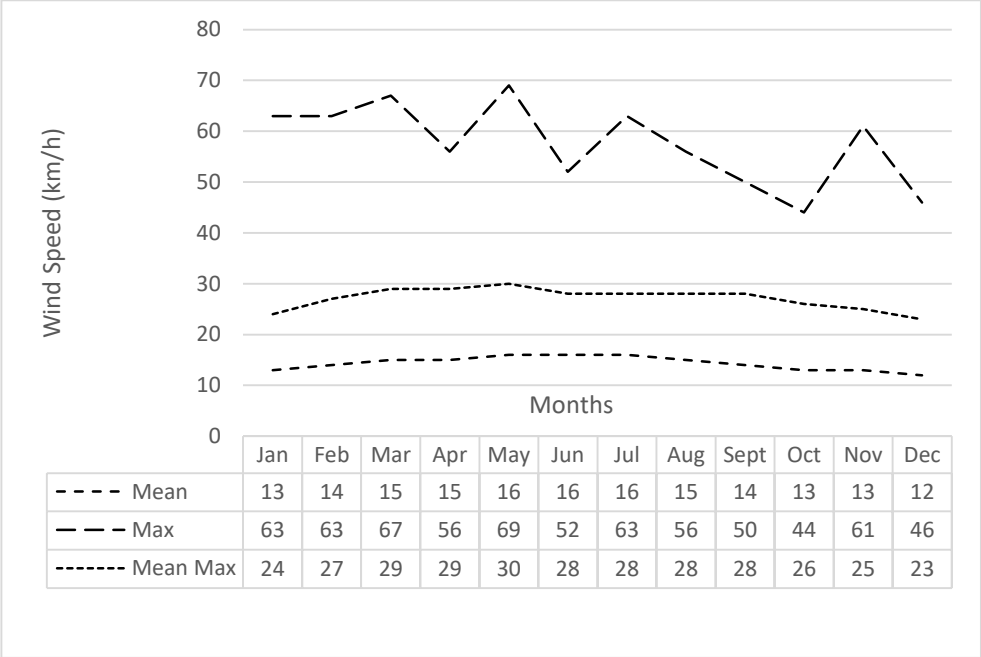
The RH ranges from 40% to 50% in summers with temperature exceeding 43 °C in the months of July & August, with the sea temperature increasing to 37 °C, and humidity averages over 80%

c) **Wind Speed:**

Wind in Dubai has varied directions, with variation in the velocities. The north-west side experiences higher wind velocities, and this can be analyzed using a wind direction study using Wind Finder software (https://www.windfinder.com/windstatistics/dubai) for the Dubai Airport weather station. Further work with Ecotech software can help develop appropriate passive strategies and comfort conditions with enhanced air movement in hot climates. Using passive strategies with thermal mass and evaporative cooling works effectively in hot-dry climates and hot humid climates, where enhanced air movement is effective [93], [94].

The graph in Figure 128 shows wind: mean, max & mean max

- Wind mean refers to the average wind speed and direction over a specified period of time, helping identify long-term wind trends.
- Wind max refers to the highest wind speed over a time, which guides the warning for dust storms (70+ Km/h) & instantaneous thunderstorm & gust (100+ Km/h)
- Wind Mean Max refers to the average of the highest wind speed over some time, which helps compare seasonal variations.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Mean	13	14	15	15	16	16	16	15	14	13	13	12
Max	63	63	67	56	69	52	63	56	50	44	61	46
Mean Max	24	27	29	29	30	28	28	28	28	26	25	23

Figure 128: Wind Speed graph for Dubai, Al Maktoum International Airport's (DWC) weather station for 2012 -2024 (Source: https://www.ncm.gov.ae/services/climate-reports-yearly)

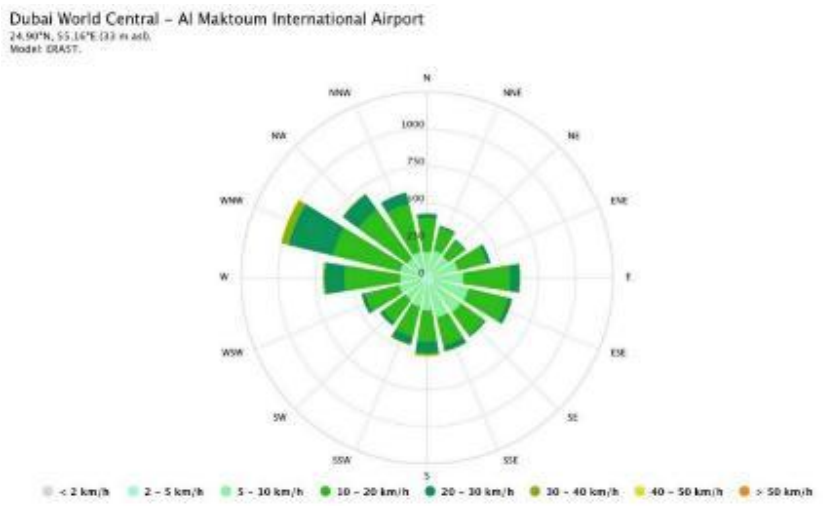


Figure 129: Wind rose Dubai, Al Maktoum International Airport's (DWC)

(Source: https://www.meteoblue.com/en/weather/historyclimate)

The wind rose diagram shows how many hours the wind blows, indicating direction per year. Dubai experiences northwesterly (NW) winds, especially during summers, due to the shamal winds blowing over Iraq and the Persian Gulf states, often strong during the day and decreasing at night. In the winters, northeasterly (NE) or southeasterly winds prevail. Most of the wind is light to moderate (9.3-27.8 km/h), and strong shamal winds (37-46 km/h) are less common and occur during sandstorms. The transitional season often features gusty and calm winds (<9.3 km/h) in the early mornings and late evenings. Wind patterns change due to obstructions at the site, such as buildings, terrain, vegetation, urban development, and the Urban Heat Island effect [38].

The desert dust storms are a concern in the UAE

This is a meteorological phenomenon widespread in arid & semi-arid regions, the dry summer season causing strong winds to lift dry loose sand particles in the desert to rise up as dust storms. This happen even at a wind speed as low as 25 miles per hour with the visibility getting greatly reduced, the air quality having the danger of particulate matter pollution increasing beyond the WHO standards *(PM2. 5, particles less than 2.5 microns or 0.0001 inch in diameter) and PM10 (particles less than 10 microns in diameter).*



Figure 130: Image: Sandstorm that engulfed the city of Dubai on April 02, 2015

(Source: https://www.khaleejtimes.com/nation/weather/uae-sandstorm-disrupts-air-traffic-in-dubai)

Dubai has seen a PM2.5 reading of 40.9 μg/m³ as a yearly average as of 2019, which is an indication of air pollution, and the heavy sandstorm blanketing the UAE adds to the pollution levels, making the situation worse during the summer months and the occurrence of north-westerly regional winds.

Figure 125 shows a dusty desert storm in April 2015 with low visibility and poor air quality. This situation occurs during every change in seasons. Mitigation measures need to be devised to maintain indoor air quality, and ventilation strategies with vegetation and dust barriers developed using green spaces need to be considered.

d) **Rainfall:**

The annual precipitation is below 100mm (4 inches). Figure 126 shows the yearly rainfall graph of Dubai, Al Maktoum International Airport's (DWC) for 2012-2024. The rains in the UAE occur as showers or downpours from December to March or April. The sea breeze circulates a large amount of water vapor to the islands during the day, which gets trapped and forms fog at night. 95% of the fog is radiation fog, prevalent in the winter, and only 5% is advection fog formed over surrounding seas and moves over the UAE.

Measured in millimeters (mm), it refers to the amount of liquid precipitation that falls from the atmosphere to the earth's surface over a specific period of time.

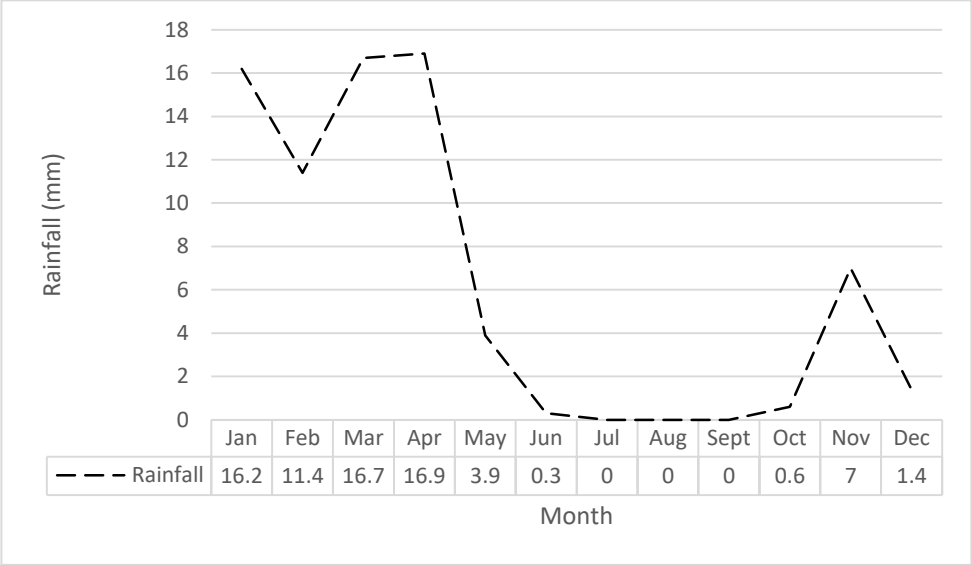


Figure 131: Rainfall graph for Dubai, Al Maktoum International Airport's (DWC) for the period 2012-2024 (Source: https://www.ncm.gov.ae/services/climate-reports-yearly)

In the UAE, artificial rain has been created since 2010 using cloud seeding, which is done by firing flares loaded with salt crystals into the convective clouds. This causes induced rain to have weather modification. Radiation fog is caused by the rapid cooling of the desert surface at night during winter [95]. The modified climate influences the seasonal weather, with unpredictable distribution of rain causing flash floods. The flood of April 2024 was a severe one in the decade [96].

e) **Solar Radiation:**

There are significant annual solar hours, with 3568 h (9.8 h/day) corresponding to a solar yearly radiation of approximately 2285 kWh/m2 (6.3 kWh/m2 per day). Incoming sunlight radiates 59% of heat equivalent into the atmosphere, with the surface radiating 12%. Solar heating happens at the surface, and radiative cooling happens in the atmosphere.

Solar radiation refers to the electromagnetic energy emitted by the sun, measured in watt-hours per square meter (Wh/m^2) for the solar energy accumulation over a given surface area over a time period. Figure 1 .10 shows the average solar radiation by month for the period 2012-2024.

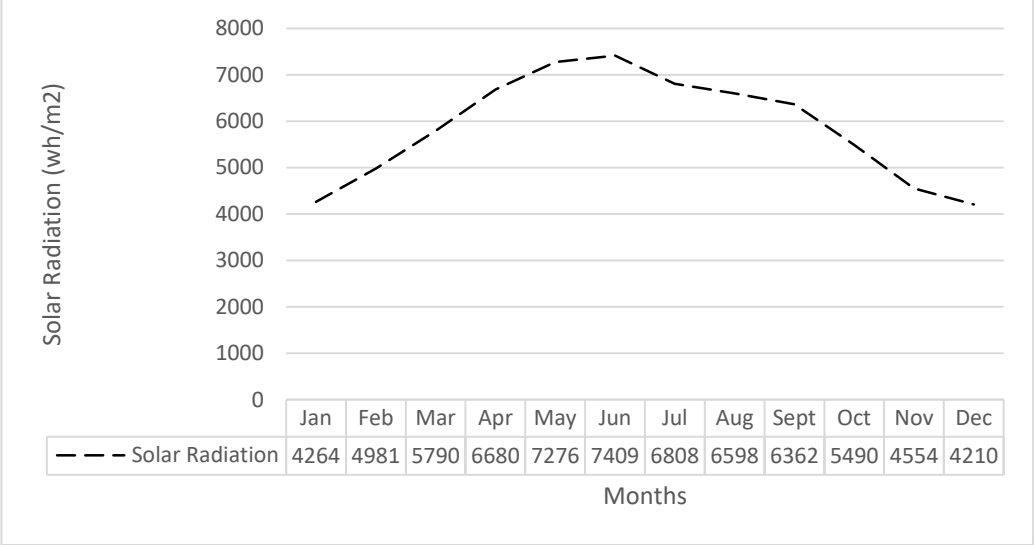


Figure 132: Solar Radiation graph for Dubai, Al Maktoum International Airport's (DWC) for the period 2012-2024 (Source: https://www.ncm.gov.ae/services/climate-reports-yearly)

The climate study is instrumental in understanding the local climatic condition for the hot desert zone of Dubai with BWh of Köppen climate classification.

BaityKool Environmental Design Principles

Integration with nature

The design incorporates vegetation on the roof, walls, courtyard, and the claustra, reducing the heat island effect, improving insulation, and creating an ecosystem with biodiversity. The courtyard connects indoors and outdoors, enhancing the occupant's physical experience by opening the large sliding folding doors facing the courtyard. The glazing maintains a pleasant visual connection with the vegetative wall, the fish tank of the aquaponics system, and the green roof. The courtyard design and connection with nature improve the occupants' well-being

Adaptability and flexibility

A modular habitat design addresses the architectural, social, and bioclimatic challenges suited for Dubai's extreme warm climate. The building features a central courtyard surrounded by its inner mass, providing shade for the exterior space. The U-shaped layout allows for natural ventilation, with warm air expelled from the courtyard to the outside. Indoor spaces are flexible, transforming from work areas to living spaces. The durable external UHPC envelope protects the structure from dust storms. The high-performance composite envelope system, designed on a compactness model,

promotes sustainability by saving materials, managing light, and adapting to harsh climatic conditions.

Climate responsiveness

The design layout, form, and building orientation suit the local climate by incorporating passive and semi-passive solutions. Additionally, the positioning of the windows and doors, along with the courtyard shaded by shading systems, reduces solar heat gain and enhances indoor thermal comfort.

Solar Control

The prototype with a closed mineral, arid outer envelope with a perforated UHPC screen acts as a solar protection screen for the external facing glazed windows. The composite multi-layered wall allows good insulation of the house indoors with the use of hygro-thermal properties for thermal comfort. The external-facing windows and doors also have roller blind sunshade with an automated BMS set according to the occupant's visual and thermal comfort. The dynamic solar pergola protects the courtyard against the sun's rays and creates a comfortable shaded environment across all seasons.

Natural Ventilation

The use of North-West wind for cross ventilation and natural night ventilation during favorable weather conditions facilitates natural cross ventilation by positioning the windows and doors. The automated Building Management System (BMS) enables the smart control of the windows in East- and West-oriented rooms, as well as the patio ventilator in the corridors. The natural air circulation indoors enhances air quality, flushes out hot air, and reduces the energy load for air conditioning during favorable outdoor weather conditions.

Day Lighting

The large size of double-glazed windows and doors reduces the need for artificial lighting indoors during the day. Using solar control glass with a low U-value reflects some of the sun's heat and decreases the amount of heat entering through the windows. Glare is minimized by using both external and internal translucent curtains as shading devices.

Thermal Mass & Insulation

A stabilized temperature indoors is maintained with the use of clay tiles as an inner lining and concrete floors to absorb, store, and release heat slowly. The bio-sourced insulation material used

for external and internal walls, roof, and floor, the composite envelope system keeps the indoors cool by preventing unwanted heat transfer during the hot climate.

Energy Efficiency & Energy Balance

The solar panels integrated into the wooden pergolas are tilted toward the south to capture maximum sunlight, while the solar panels on the east, west, and south walls generate additional energy from morning to evening. Additionally, to conserve energy, passive control measures are implemented alongside the active home automation system to open and close windows and blinds, managing the natural airflow indoors.

Water Conservation

The gray water at the prototype is treated with Lumbrifilter, an organic filter, and a bio-solar purification system. The filtered water is reused for irrigating the roof plants, patio, and aquaponics system—a vertical farm with a fish tank embedded into the wall separating the courtyard and corridor.

Material Selection

Eco-friendly materials are used to consider the thermal properties of the materials, aiming to achieve the best comfort for the inhabitants. The thermal efficiency reduces its energy consumption, making it eco-friendly and energy-wise.

Appendix C – Thermal characteristics of BaityKool Envelope System

The BaityKool prototype envelope system is composed of Bio-sourced materials with the wall composition details as indicated in Fig. 133, and the Thermal and optics characteristics as indicated in Table 63 to 69:

Wall Composition: High-performance wall layering

1. UHPC (Ultra High Performance Fiber Concrete) Panel hung from roof
2. Air Gap
3. Rain/ Vapor/ Reflective barrier
4. Rigid insulation
5. Semi-rigid insulation + Wood Vertical stiffeners
6. Structural Cross Laminated timber panel
7. Compressed Mud bricks
8. Acoustic tensed Canvas

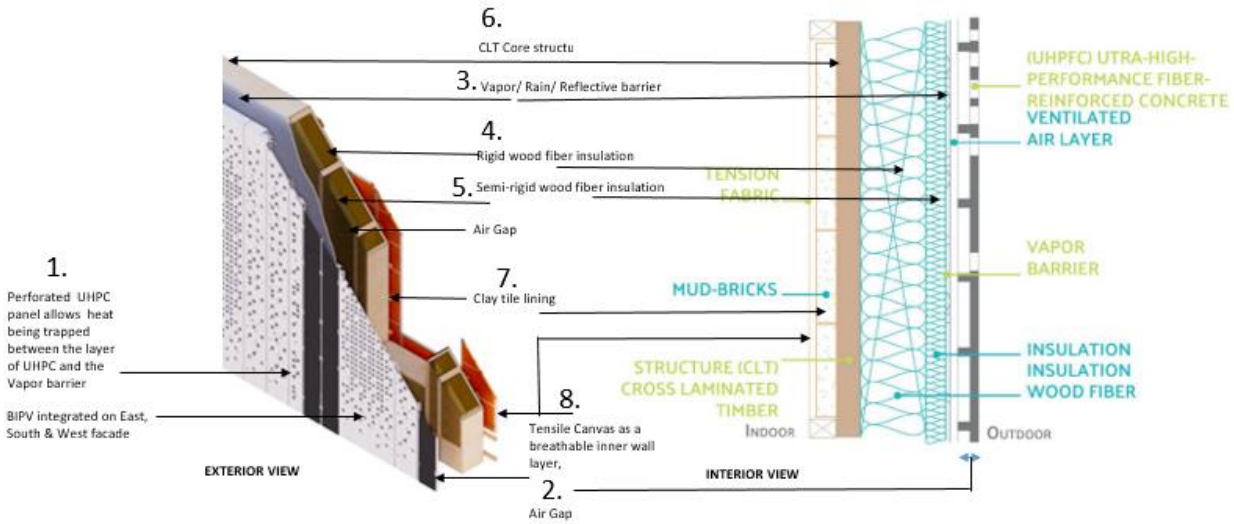


Figure 133: BaityKool Envelope Wall System [22], [85].

Table 63: Thermal characteristics of External Structural Wall at BaityKool prototype

STRUCTURAL WALLS (Walls/ EXT.) – EXTERNAL WALLS						
	Conductivity W/(m.K)	Density Kg/m³	Heat capacity J(kg.K)	Thickness cm	Density Kg/m³	R m³.K/W
Raw Clay	0.750	2000	900	3.5	70.0	0.05
CLT Panel	0.130	400	1600	6.0	24.0	0.46
Wood Floor Insulation	0.036	60	2100	21.0	12.6	5.83
Reflective and Waterproof Membrane	0.001	10	0	0.1	0.0	1.70
Total	-	-	-	30.6	106.6	8.04

Table 64: Thermal characteristics of Non- Structural Wall at BaityKool prototype

NON-STRUCTURAL WALLS (Interior Walls) – INTERNAL WALLS						
	Conductivity W/(m.K)	Density Kg/m³	Heat capacity J(kg.K)	Thickness cm	Density Kg/m³	R m³.K/W
Plywood Panel	0.130	632	2000	2.5	15.8	0.19

Recycled Cotton Insulation	0.036	60	2100	5.0	3.0	1.39
Plywood Panel	0.130	632	2000	2.5	15.8	0.19
Total	-	-	-	10.0	34.6	1.77

Table 65: Thermal characteristics of Flat roof at BaityKool prototype

FLAT ROOF (Flat roof) – ROOF TERRACE						
	Conductivity W/(m.K)	Density Kg/m³	Heat capacity J(kg.K)	Thickness cm	Density Kg/m³	R m³.K/W
Plywood Panel	0.130	632	2000	2.0	12.6	0.15
Cellulose Wadding Insulation	0.036	60	2100	23.0	13.8	6.39
CLT Panel	0.130	400	1600	5.0	20.0	0.38
Waterproof Membrane	0.250	1200	2000	0.1	1.2	0.00
Total	-	-	-	30.1	47.6	6.93

Table 66:Thermal characteristics of Pitched roof at BaityKool prototype

ROOF (Pitched roof) – PITCHED ROOF						
	Conductivity W/(m.K)	Density Kg/m³	Heat capacity J(kg.K)	Thickness cm	Density Kg/m³	R m³.K/W
Plywood Panel	0.130	632	2000	2.0	12.6	0.15
Cellulose Wadding Insulation	0.036	60	2100	23.0	13.8	6.39
CLT Panel	0.130	400	1600	5.0	20.0	0.38
Waterproof Membrane	0.250	1200	2000	0.1	1.2	0.00
Raw earth	0.750	2000	900	12.0	240.0	0.16
Total	-	-	-	43.1	291.6	7.17

Table 67:Thermal characteristics of Floor at BaityKool prototype

LOWER FLOOR (Ground) – FLOOR						
	Conductivity W/(m.K)	Density Kg/m³	Heat capacity J(kg.K)	Thickness cm	Density Kg/m³	R m³.K/W
Waterproof membrane	0.250	1200	2000	0.1	1.2	0.00
Plywood Panel	0.130	632	2000	2.0	12.6	0.15
Recycled Wood Insulation	0.036	60	2100	20.0	12.0	5.56
CLT Panel	0.130	400	1600	6.0	24.0	0.46
Concrete	2.299	2350	1000	5.0	117.5	0.02
Total	-	-	-	35.1	167.3	6.20

Table 68: Thermal characteristics of Patio Window at BaityKool prototype

PATIO WINDOW		
Glazing	44.2(16)44.2: PLANITHERM SGG ULTRA N/N II Thermal Glass	
Frame	Wood	
Opaque Infill	Wood	
Protection	External Blinds	
Component	Description	
Glazing	44.2(16)44.2: SGG STADIP Protect et SGG STAPID Protect PLANTHERM ULTRA N Face 3	
	U_g	1,100 W/(m².K)
	TL_g	76%
	RL_g	12%
	$SG_{g.C}$	53%
	$SG_{g.E}$	54%
Frame	Wood	
	U_f	3,000 W/(m².K)

	P_f	50%
	P_{th}	40%
Opaque Infill	Wood	
	U_p	3,000 W/(m².K)
	P_v	40%
	P_{th}	40%

Table 69: Thermal characteristics of External Window at BaityKool prototype

EXTERNAL WINDOW		
Glazing	4(16)4: SGG ECLAZ ONE	
Frame	Wood	
Opaque Infill	Wood	
Protection	External Blinds	
Component	Description	
Glazing	4(16)4: SGG ECLAZ ONE	
	U_g	1,100 W/(m².K)
	TL_g	80%
	RL_g	12%
	$SG_{g.C}$	59%
	$SG_{g.E}$	59%
Frame	Cadre en bois performat	
	U_f	3,000 W/(m².K)
	P_f	50%
	P_{th}	40%
Opaque Infill	Remplissage en bois	
	U_p	3,000 W/(m².K)
	P_v	40%
	P_{th}	40%

Protection	Store venetian ext.			
	Type		Store venitien	
	Position		Outside	
	Space between the blades		0.100m	
	Blade tilt		0.100m	
	Distance		30.00°	
	Pilotage		5.00cm	
	ΔR		Sun tracking	
	$T_{v,ext}$	0%	$T_{v,int}$	0%
	$P_{v,ext}$	95%	$P_{v,int}$	95%
	$T_{e,ext}$	0%	$T_{e,int}$	0%
$P_{e,ext}$	95%	$P_{e,int}$	95%	

Appendix D: Experimental analysis of Solar Shading indoor effects

Analysis of solar shading performance for RBB with temperature measured at 6-hour intervals for 48 hours during the experiment.

- **Indoor air Temperature (°C) Action Benefits with Solar Shading: RBB at 6 hours interval in July 2023**

Table 70: Indoor air Temperature (°C) $\Delta\, T^{Room}_{air,\ ACTION\ Benefits}$ *(cf. section 3.6.1, Eq 2, Eq3 & Eq.4) at 6 hours interval during the Ref. & Exp. SS: RBB days in July*

t	**Ext. T(°C) 17 & 18 July 23**	**Ref. T (°C) Liv. 17 & 18 July 23**	**Diff. T (°C) Liv. 17 & 18 July 23 (Ref)**	**Ext. (T) (°C) 15 & 16 July 23**	**Exp. SS:RBB T (°C) Liv. 15 & 16 July 23**	**Exp.SS:RBB Diff . T (°C) Liv. 15 & 16 July 23**	**T (°C) Benefit. (Exp. SS:RBB) (Liv.) 15 & 16 July 23**
6:00	33.3	33.9	**0.68**	37.6	29.3	**-8.2**	**-9**
12:00	46.4	36.4	**-9.95**	47.6	29.9	**-17.6**	**-8**
18:00	41.4	36.1	**-5.25**	44.4	30.3	**-14.0**	**-9**
0:00	35.5	36.0	**0.53**	39.3	29.6	**-9.6**	**-10**
6:00	31.8	36.3	**4.55**	36.1	29.5	**-6.6**	**-11**
12:00	46.6	37.0	**-9.54**	48.0	30.7	**-17.2**	**-8**
18:00	40.6	36.1	**-4.49**	43.1	31.2	**-11.8**	**-7**
0:00	35.3	34.3	**-1.00**	37.4	32.7	**-4.6**	**-4**
6:00	33	33.3	**0.35**	33.3	33.9	**0.6**	**0**

- **Indoor air Temperature (°C) Action Benefits with Solar Shading: RBB at 6 hours interval in August 2023**

Table 71: Indoor air Temperature (°C) $\Delta T^{Room}_{air,\ ACTION\ Benefits}$ (cf. section 3.6.1, Eq 2, Eq3 & Eq.4) at 6-hour intervals during the Ref. & Exp. SS: RBB days.in August

t	Ext. T(°C) 22 & 23 Aug. 23	Ref. T (°C) Liv. 22 & 23 Aug. 23	Diff. T (°C) Liv. 22 & 23 Aug. 23	Ext. (T) (°C) 25 & 26 Aug. 23	Exp. SS:RBB T (°C) Liv. 25 & 26 Aug. 23	Exp.SS:RBB Diff . T (°C) Liv 25 & 26 Aug. 23	T (°C) Benefit. (Exp. SS:RBB) (Liv.) 25 & 26 Aug. 23
6:00	30.7	27.5	**-3.1**	35.0	28.8	**-6.1**	**-3**
12:00	45.9	27.3	**-18.5**	51.1	28.5	**-22.5**	**-4**
18:00	40.3	28.9	**-11.3**	41.4	29.9	**-11.4**	**0**
0:00	34.9	29.4	**-5.4**	36.9	29.2	**-7.6**	**-2**
6:00	31.8	30.9	**-0.8**	33.7	28.2	**-5.4**	**-5**
12:00	44.9	30.7	**-14.1**	49.4	27.6	**-21.7**	**-8**
18:00	40.2	29.8	**-10.3**	42.6	28.8	**-13.7**	**-3**
0:00	35.2	29.6	**-5.5**	36.9	28.2	**-8.6**	**-3**
6:00	33.1	30.3	**-2.7**	32.9	27.1	**-5.7**	**-3**

- **Indoor air Temperature (°C) Action Benefits with Solar Shading: RBB at 6 hours interval in September 2023**

Table 72: Indoor air Temperature (°C) $\Delta T^{Room}_{air,\ ACTION\ Benefits}$ (cf. section 3.6.1, Eq 1, Eq2 & Eq.3) at 6 hours interval during the Ref. & Exp. SS:RBB days. in September

t	Ext. T(°C) 20 & 21 Sept. 23	Ref. T (°C) Liv. 20 & 21 Sept. 23	Diff. T (°C) Liv. 20 & 21 Sept. 23	Ext. (T) (°C) 23 & 24 Sept. 23	Exp. SS:RBB T (°C) Liv. 23 & 24 Sept. 23	Exp.SS:RBB Diff . T (°C) Liv 23 & 24 Sept. 23	T (°C) Benefit. (Exp. SS:RBB) (Liv.) 23 & 24 Sept. 23.
6:00	33.7	31.6	**-2.0**	30.6	29.7	**-0.8**	**1**
12:00	44.8	31.4	**-13.3**	46.6	29.9	**-16.6**	**-3**
18:00	39.6	30.6	**-8.9**	40.2	28.8	**-11.3**	**-2**
0:00	34.1	30.2	**-3.8**	34.4	28.1	**-6.2**	**-2**
6:00	30.8	31.1	**0.3**	32.1	28.5	**-3.5**	**-4**
12:00	44.6	31.0	**-13.5**	45.1	29.0	**-16.0**	**-3**
18:00	38.8	30.3	**-8.4**	40.0	28.0	**-11.9**	**-3**
0:00	34.4	29.6	**-4.7**	34.9	27.7	**-7.1**	**-2**
6:00	30.6	30.3	**-0.2**	31.8	29.0	**-2.7**	**-2**

Analysis of fluctuations in temperature (T) and relative humidity (RH) under reference and experimental conditions. SS: RBB days for East- and West-oriented rooms.

- **Indoor air temperature fluctuations in 6-hour interval regarding East-oriented living (Liv.) and West-oriented bedroom (BRm.) on reference days without shading and experimental days with SS: RBB in July 2023**

Table 73: Indoor air temperature fluctuation ($\Delta T^{Room}_{air,REF}$) & ($\Delta T^{Room}_{air,EXP}$) (cf. section 3.6.1, Eq 5 & Eq.6) in 6-hour intervals showing the effect of solar shading on East-facing Liv. & West facing BRm.

Time (t) Hrs.	Ref. Liv. East Oriented T (°C) 17 & 18 July 23	T (°C) Fluc. Liv (Ref.)	Exp. Liv. T (°C) East Oriented 15 & 16 July 23	T (°C) Fluc. (Exp. SS RBB)	Ref. BRm. T (°C) West Oriented 17 & 18 July 23	T (°C) Fluc. BRm. (Ref.)	Exp. BRm. T (°C) West Oriented 15 & 16 July 23	T (°C) Fluc. BRm. (Exp. RBB)
6:00	33.9	0	29.3	0	33.4	0	30.1	0
12:00	36.4	2.47	29.9	0.54	35.9	2.43	30.8	0.7
18:00	36.1	-0.30	30.3	0.41	36.2	0.30	30.8	0.0
0:00	36.0	-0.12	29.6	-0.73	35.9	-0.24	30.3	-0.5
6:00	36.3	0.31	29.5	-0.11	36.5	0.53	29.8	-0.5
12:00	37.0	0.71	30.7	1.28	37.6	1.16	32.2	2.4
18:00	36.1	-0.95	31.2	0.45	36.0	-1.63	31.7	-0.4
0:00	34.3	-1.81	32.7	1.50	34.5	-1.53	32.5	0.8
6:00	33.3	-0.95	33.9	1.25	34.1	-0.31	33.4	0.9

Note: The (+Ve) indicates T rise with a higher value than the previous interval hour & (-Ve) indicates T drop with a lower value than the last hour interval.

- **Indoor Relative Humidity fluctuations in 6-hour interval regarding East-oriented living (Liv.) and West-oriented bedroom (BRm.) on reference days without shading and experimental days with SS: RBB in July 2023**

Table 74: RH fluctuation ($\Delta RH^{Room}_{air,REF}$) & ($\Delta RH^{Room}_{air,EXP}$) (cf. section 3.6.1, Eq 7 & Eq.8) in 6 hours intervals on Ref. & Exp. SS:RBB in July

Time (t) Hrs.	Ref. Liv. (RH) 17 & 18 July 23	RH (%) Fluc., in 6 Hrs. Liv. (Ref.)	Exp. Liv. (RH) 15 & 16 July 23	RH (%) Fluc, in 6 Hrs. Liv. (Exp.SS:RBB)	Ref. BRm. (RH) 17 & 18 July 23	RH (%) Fluc, in 6 Hrs. BRm. (Ref.)	Exp. BRm. (RH) 15 & 16 July 23	RH (%) Fluc, in 6 Hrs. BRm. (Exp.SS:RBB)
6:00	53	0	61	0	67	0	75	0
12:00	56	3	60	-1	70	3	72	-2
18:00	56	0	62	2	66	-4	75	2
0:00	58	2	62	0	69	2	75	0
6:00	57	-1	60	-2	67	-1	73	-2
12:00	56	-1	60	0	67	0	68	-5

18:00	61	5	61	1	74	7	74	7
0:00	62	1	58	-3	75	1	73	-2
6:00	62	0	53	-5	74	-1	67	-6

Note: The (+Ve) indicates T rise with higher value than the previous interval hour & (-Ve) indicates T drop with lower value than the previous interval hour.

- **Indoor air temperature fluctuations in 6-hour interval regarding East-oriented living (Liv.) and West-oriented bedroom (BRm.) on reference days without shading and experimental days with SS: RBB in August 2023**

Table 75: Indoor air temperature fluctuation ($\Delta T^{Room}_{air,REF}$) & ($\Delta T^{Room}_{air,EXP}$) (cf. section 3.6.1, Eq 5 & Eq.6) in 6 hours intervals showing the effect of solar shading on East facing Liv. & West facing BRm in August

Time (t) Hrs.	Ref. Liv. (T) 22 & 23 Aug. 23	T (°C) Fluc. Liv. (Ref.)	Exp. Liv. (T) 25 & 26 Aug. 23	T (°C) Fluc. Liv. (Exp. SS:RBB)	Ref. BRm. (T) 22 & 23 Aug. 23	T (°C) Fluc. BRm. (Ref.)	Exp. BRm. (T) 25 & 26 Aug. 23	T (°C) Fluc. BRm. (Exp. SS:RBB)
6:00	27.5	0	28.8	0	28.0	0	29.2	0
12:00	27.3	-0.2	28.5	-0.3	28.3	0.3	29.0	-0.2
18:00	28.9	1.5	29.9	1.4	29.9	1.6	30.4	1.3
0:00	29.4	0.4	29.2	-0.6	29.5	-0.4	29.7	-0.6
6:00	30.9	1.5	28.2	-0.9	29.0	-0.4	28.7	-1.0
12:00	30.7	-0.2	27.6	-0.6	30.0	1.0	28.3	-0.3
18:00	29.8	-0.9	28.8	1.1	31.9	1.8	29.5	1.1
0:00	29.6	-0.1	28.2	-0.5	31.0	-0.9	28.8	-0.6
6:00	30.3	0.7	27.1	-1.0	30.1	-0.9	27.7	-1.1

Note: The (+Ve) indicates T rise with higher value than the previous interval hour & (-Ve) indicates T drop with lower value than the previous interval hour.

- **Indoor Relative Humidity fluctuations in 6-hour interval regarding East-oriented living (Liv.) and West-oriented bedroom (BRm.) on reference days without shading and experimental days with SS: RBB in August 2023**

Table 76: RH fluctuation ($\Delta RH^{Room}_{air,REF}$) & ($\Delta RH^{Room}_{air,EXP}$) (cf. section 3.6.1, Eq 7 & Eq.8) in 6 hours intervals on Ref. & Exp. SS:RBB in August

Time (t) Hrs.	Ref. Liv. (RH) 22 & 23 Aug. 23	RH (%) Fluc., Liv. (Ref.)	Exp. Liv. (RH) 25 & 26 Aug. 23	RH (%) Fluc., Liv. (Exp. SS:RBB)	Ref. BRm. (RH) 22 & 23 Aug. 23	RH (%) Fluc., BRm. (Ref.)	Exp. BRm. (RH) 25 & 26 Aug. 23	RH (%) Fluc., BRm. (Exp. SS:RBB)
6:00	72	0	73	0	70	0	70	0
12:00	68	-4	70	-3	64	-6	67	-3
18:00	75	7	75	5	66	3	72	5
0:00	73	-2	73	-2	73	7	70	-2
6:00	75	2	71	-1	74	1	69	-1
12:00	75	0	68	-3	70	-4	65	-4
18:00	74	-1	72	4	71	1	69	4
0:00	74	0	71	-1	73	2	68	-1
6:00	75	1	69	-2	73	-1	66	-2

- **Indoor air temperature fluctuations in 6-hour interval regarding East-oriented living (Liv.) and West-oriented bedroom (BRm.) on reference days without shading and experimental days with SS: RBB in September 2023**

Table 77: Indoor air temperature fluctuation ($\Delta T_{air,REF}^{Room}$) & ($\Delta T_{air,EXP}^{Room}$) (cf. section 3.6.1, Eq 5 & Eq.6) in 6 hours intervals showing the effect of solar shading on East facing Liv. & West-facing BRm. in September

Time (t) Hrs.	Ref. Liv. (T) 20 & 21 Sept. 23	T (°C) Fluc. Liv. (Ref.) in 6 Hrs.	Exp. Liv. (T) 23 & 24 Sept. 23	T (°C) Fluc. Liv. (Exp.SS:RBB) in 6 Hrs.	Ref. BRm. (T) 20 & 21 Sept. 23	T (°C) Fluc. BRm. (Ref.) in 6 Hrs.	Exp. BRm. (T) 23 & 24 Sept. 23	T (°C) Fluc. BRm. (Exp.SS:RBB) in 6 Hrs.
6:00	31.6	0	29.7	0	31.2	0	29.0	0
12:00	31.4	-0.2	29.9	0.2	31.0	-0.2	29.3	0.3
18:00	30.6	-0.7	28.8	-1.1	30.1	-0.8	28.1	-1.2
0:00	30.2	-0.4	28.1	-0.7	29.5	-0.5	27.3	-0.8
6:00	31.1	0.9	28.5	0.4	30.7	1.1	28.0	0.7
12:00	31.0	-0.1	29.0	0.4	30.5	-0.2	28.5	0.4
18:00	30.3	-0.7	28.0	-0.9	29.7	-0.7	27.5	-1.0
0:00	29.6	-0.6	27.7	-0.3	28.9	-0.8	27.0	-0.4
6:00	30.3	0.6	29.0	1.3	29.7	0.7	28.7	1.6

Note: The (+Ve) indicates T rise with higher value than the previous interval hour & (-Ve) indicates T drop with lower value than the previous interval hour.

- **Indoor Relative Humidity fluctuations in 6-hour interval regarding East-oriented living (Liv.) and West-oriented bedroom (BRm.) on reference days without shading and experimental days with SS: RBB in September 2023**

Table 78: RH fluctuation (Δ RH $^{Room}_{air,REF}$) & (Δ RH $^{Room}_{air,EXP}$) (cf. section 3.6.1, Eq 6 & Eq.7) in 6-hour intervals on Ref. & Exp. SS:RBB in September.

Time (t) Hrs.	Ref. Liv. (RH) 20 & 21 Sept. 23	RH (%) Fluc. Liv. (Ref.) in 6 Hrs	Exp. Liv. (RH) 23 & 24 Sept. 23	RH (%) Fluc. Liv. (Exp.SS: RBB) in 6 Hrs	Ref. BRm. (RH) 20 & 21 Sept. 23	RH (%) Fluc. BRm. (Ref.) in 6 Hrs	Exp. BRm. (RH) 23 & 24 Sept. 23	RH (%) Fluc. (Exp.SS:RBB) in 6 Hrs
6:00	54	0	51	0	66	0	63	0
12:00	56	2	54	3	69	2	67	3
18:00	55	-1	51	-3	68	-1	63	-4
0:00	54	-1	51	0	68	0	63	0
6:00	55	1	48	-3	69	1	57	-6
12:00	57	2	52	4	70	1	64	7
18:00	56	-1	49	-3	70	0	60	-5
0:00	56	0	48	-1	70	0	60	0
6:00	57	1	51	3	72	2	63	3

Note: The (+Ve) indicates RH % rise with higher value than the previous interval hour & (-Ve) indicates RH % drop with lower value than the previous interval hour.

Appendix E: Experimental analysis of Natural Ventilation indoor effects

Table 79: External Temperature, Relative Humidity, Wind Speed, and Wind Direction at BaityKool Lab site context for baseline Reference and Experiment DV+NV days with 3-hour intervals in January for 24 hours

Time (t) Hrs.	Ref. Ext T (°C) 15 & 16 JAN 24	Relative Humidity (%) 15 & 16 JAN 24	Wind Speed 15 & 16 JAN 24	Wind Direction 15 & 16 JAN 24	Time (t) Hrs.	Exp. Ext. T (°C) 17 & 18 Jan 24	Relative Humidity (%) 17 & 18 Jan 24	Wind Speed 17 & 18 Jan 24	Wind Direction 17 & 18 Jan 24
6:00	16.6	58	0	---	6:00	20.8	77	0	SW
9:00	21.4	38	0	SE	9:00	23.1	74	0.4	SW
12:00	32.0	13	1.3	SW	12:00	29.9	32	1.8	WSW
15:00	34.0	13	1.3	WSW	15:00	29.5	29	2.7	WSW
18:00	28.5	32	0	WSW	18:00	25.1	44	4	WSW
21:00	23.5	60	0	---	21:00	23.4	49	2.2	WSW
0:00	20.1	66	0	WSW	0:00	22.8	50	2.7	WSW
3:00	17.4	59	0	WSW	3:00	21.2	54	0	WSW
6:00	16.6	60	0.4	SSW	6:00	18.8	62	0.9	S

Table 80: Difference in indoor air Temperature (°C) $\Delta T^{Room}_{air,\ ACTION\ Benefits}$ (cf. section 3.6.1, Eq 1, Eq2 & Eq.3) at 6 hours interval during the Ref. & Exp. DV + NV days. in January for 48 hours

t	Ref. Ext. T(°C) 15& 16 Jan	Ref. Liv. T (°C) East Orientation 15 & 16 Jan	Diff T (°C) 15 & 16 Jan	Exp. Ext. T(°C) 17& 18 Jan	Exp. Liv. T(°C) East Oriented 17 & 18 Jan	Diff T(°C) 17 & 18 Jan	T (°C) Benefit. in Liv. East Oriented 17 & 18 Jan with EXP-DV+NV
6:00	16.6	23.1	**6.53**	20.8	23.9	**3.15**	**-3.3**
12:00	32	22.9	**-9.02**	29.9	22.8	**-7.08**	**1.9**
18:00	28.5	22.8	**-5.66**	25.1	23.3	**-1.72**	**3.9**
0:00	20.1	23.8	**3.74**	22.8	24.3	**1.50**	**-2.2**
6:00	16.6	24.3	**7.71**	18.8	24.4	**5.63**	**-2.0**
12:00	29.8	24.4	**-5.33**	28.6	24.2	**-4.38**	**0.9**
18:00	27.5	24.4	**-3.10**	25	24.0	**-0.91**	**2.1**
0:00	23.3	26.4	**3.10**	20.6	24.8	**4.23**	**1.1**
6:00	20.8	23.9	**3.15**	18.6	24.9	**6.32**	**3.1**

Note: **(-Ve)** indicated the potential T °C reduction, **(+Ve)** indicated the potential T °C increase

- **Indoor air temperature fluctuations at 3-hour intervals at Liv. & BRm. during EXP. DV+NV days**

Table 81: Indoor air temperature fluctuation between REF and EXP with Day ventilation and Night ventilation (DV+NV) for East-oriented living and West-oriented in January.

Time (t) Hrs.	Ref. Liv. T(°C) 15 & 16 JAN 24	Diff in T(°C) in 3 hour interval	Exp. DV+NV Liv. T (°C) 17 & 18 Jan 24	Diff in T(°C) in 3 hour interval	Ref. BRm. T(°C) 15 & 16 JAN 24	Diff in T(°C) in 3 hour interval	Exp. DV +NV BRm. T(°C) 17 & 18 Jan 24	Diff in T (°C) in 3-hour interval	Wind Direction 17 & 18 Jan 24
6:00	23.1	0.00	23.9	0.0	23.3	0.0	23.0	0.0	SW
9:00	23.1	0.02	23.4	-0.4	23.3	-0.0	22.6	-0.3	SW
12:00	22.9	-0.17	22.8	-0.6	23.1	-0.1	22.5	-0.1	WSW
15:00	22.8	-0.12	22.9	0.1	22.9	-0.2	22.8	0.2	WSW
18:00	22.8	-0.02	23.3	0.4	22.8	-0.0	23.1	0.3	WSW
21:00	23.2	0.41	23.8	0.4	23.4	0.5	23.6	0.5	WSW
0:00	23.8	0.59	24.3	0.4	24.2	0.8	24.3	0.	WSW
3:00	24.2	0.40	24.4	0.1	24.5	0.3	24.5	0.	WSW
6:00	24.3	0.07	24.4	-0.0	24.5	-0.0	24.4	-0.1	S

Note: The (+Ve) – indicates indoor air temperature rise wit a higher value than the previous interval hour & (-Ve) – indicates indoor air temperature drop with a lower value than the previous interval hour.

- **Potential temperature reduction with Natural Ventilation (Nv) action: Night Ventilation (NV) during 48 hours of experiment**

Table 82: Difference in indoor air Temperature (°C) $\Delta T^{Room}_{air,\ ACTION\ Benefits}$ *(cf. section 3.6.1, Eq 1, Eq2 & Eq.3) at 6 hours interval during the Ref. & Exp. NV days. in January for 24 hours*

t	Ref. Ext. T (°C) 10 Jan 2024	Ref. Liv. (T) 10 Jan 2024	Diff T (°C) 10 Jan 2024	Exp. Ext . T(°C) 13 Jan 2024	Exp. Liv. T(°C) 13 Jan 2024	Diff T(°C) 13/01/24	T (°C) Benefit. Liv. with EXP – NV , 13 Jan 2024
18:00	25.3	22.9	**-2.3**	25.3	19.5	**-5.7**	**-3**
0:00	19.7	23.6	**3.9**	18.4	21.2	**2.7**	**-1**
6:00	16.7	23.9	**7.1**	15.6	21.8	**6.1**	**-1**
12:00	27.7	23.5	**-4.2**	28.7	19.4	**-9.2**	**-5**
18:00	24.6	23.2	**-1.4**	25.9	19.7	**-6.1**	**-5**

Table 83: Difference in indoor air Temperature (°C) $\Delta T^{Room}_{air,\ ACTION\ Benefits}$ *(cf. section 3.6.1, Eq 1, Eq2 & Eq.3) at 6 hours interval during the Ref. & Exp. NV days. in April for 24 hours*

t	Ref. Ext. T (°C) , 3 April 2024	Ref. Liv. T(°C) , 3 April 2024	Diff T (°C) 03/04/24	Exp. Ext. T(°C), 6 April 2024	Exp. Liv. T(°C), 6 April 2024	Diff T(°C), 6 April 2024	T (°C) Benefit. Liv with EXP – NV, 6 April 2024
18:00	31.5	25.6	**-5.8**	32.2	24.0	**-8.20**	**-2**
0:00	24.1	26.8	**2.7**	24.1	25.9	**1.87**	**-1**
6:00	20.8	26.9	**6.17**	19.6	26.5	**6.92**	**1**
12:00	33.6	26.8	**-6.76**	32.7	26.2	**-6.42**	**0**
18:00	32.3	26.5	**-5.76**	33.2	26.6	**-6.54**	**-1**

Note: **(-Ve)** indicated the potential indoor air temperature °C reduction, **(+Ve)** indicated the potential indoor air temperature °C increase

- **Indoor air temperature fluctuations on Ref. & Exp. NV days at Liv. Oriented East in January 2024**

Table 84: Indoor air temperature fluctuation ($\Delta T^{Room}_{air,\ REF}$ *) &* $\Delta T^{Room}_{air,\ EXP}$ *) (cf. section 3.6.1, Eq 4 & Eq.5) in 3-hour intervals showing the effect of Night Ventilation (NV) on the east-facing Liv. and west-facing BRm. in January.*

Time (t) Hrs.	Ref. Liv. T (°C) , 10 Jan 24	Diff in T(°C) , in 3 Hrs. Inerval	Exp. NV Liv. T(°C), 13 Jan 24	Diff in T(°C) , in 3 Hrs Interval.	Ref. BRm. T(°C) , 10 Jan 24	Diff in T(°C) , in 3 Hrs. Interval	Exp. NV BRm. T(°C) , 13 Jan 24	Diff in T(°C) , in 3 Hrs. Interval	Wind Direction
18:00	22.9	**0**	19.5	0	22.9	0	19.7	0	WSW
21:00	23.2	0.33	20.4	0.95	23.3	0.41	20.7	0.96	---

0:00	23.6	0.33	21.1	0.6	23.9	0.5	21.6	0.8	---
3:00	23.8	0.25	21.6	0.4	4.0	0.1	21.9	0.3	---
6:00	23.8	0.03	21.7	0.1	23.9	-0.1	21.94	-0.0	---
9:00	23.7	-0.14	20.1	-1.6	23.8	-0.1	20.86	-1.0	ESE
12:00	23.4	-0.2	19.4	-0.7	23.5	-0.2	19.94	-0.9	SW
15:00	23.2	-0.2	18.5	-0.8	23.2	-0.3	19.01	-0.9	WSW
18:00	23.1	-0.0	19.7	1.1	23.1	-0.13	19.88	0.8	---

Appendix F: Experimental analysis of natural Night Ventilation and Solar Shading indoor effects

Table 85: Difference in indoor air Temperature (°C) $\Delta T^{Room}_{air,\ ACTION\ Benefits}$ (cf. section 3.6.1, Eq. 2, Eq.3 & Eq.4) at 6-hour intervals during the Ref. & Exp. NV+SS: RBB in March for 48 hours

t	Ref. Ext. T(°C) , 13 & 14 Mar. 24	Ref. Liv. T(°C) , 13 & 14 Mar. 24	Diff T(°C) , Liv. 13 & 14 Mar. 24	Exp.Ext. T(°C) , 15 & 16 Mar. 24	Exp. Liv. T(°C) , 15 & 16 Mar. 24	Diff T(°C) , 15 & 16 Mar. 24	T (°C) Benefit. Liv. with EXP - NV+SS 15 & 16 Mar. 24
6:00	17.9	26.1	**8.2**	21.4	27.4	**6.0**	**-2.2**
12:00	31	26.0	**-4.9**	34.9	24.0	**-10.8**	**-5.8**
18:00	28.2	25.9	**-2.2**	30	24.7	**-5.2**	**-2.9**
0:00	23.3	26.8	**3.5**	23.9	26.1	**2.2**	**-1.3**
6:00	20.3	26.9	**6.6**	21.6	26.7	**5.1**	**-1.5**
12:00	32.3	26.8	**-5.4**	36.2	25.0	**-11.1**	**-5.6**
18:00	30.1	26.8	**-3.2**	31.9	25.9	**-5.9**	**-2.7**
0:00	24.3	27.5	**3.2**	26.4	27.4	**1.04**	**-2.2**
6:00	21.4	27.4	**6.0**	24.2	28.0	**3.83**	**-2.2**

- **Indoor air Temperature fluctuations at 3-hour intervals at Liv. & BRm during Exp. NV+SS:RBB days in March 2024**

Table 86: Indoor air temperature fluctuation ($\Delta T^{Room}_{air,\ REF}$) & ($\Delta T^{Room}_{air,\ EXP}$) (cf. section 3.6.1, Eq 4 & Eq.5) in 6 hours interval showing the effect of Exp. NV+SS:RBB on the east-facing Liv. and west-facing BRm. in March

Time (t) Hrs.	Ref. Liv. (T) 13 & 14 Mar. 24	Diff. in T in 3 Hrs.	Exp. Liv. (T) 15 & 16 Mar. 24	Diff. in T in 3 Hrs.	Ref. BRm. (T) 13 & 14 Mar. 24	Diff. in T in 3 Hrs.	Exp. BRm. (T) 15 & 16 Mar. 24	Diff. in T in 3 Hrs.	Wind Direction
6:00	26.1	0	27.4	0	26.2	0	27.5	0	ENE
12:00	26.0	-0.1	24.0	-3.3	25.9	-0.25	24.4	-3.0	NE

18:00	25.9	-0.0	24.7	0.7	25.9	-0.0	24.6	0.2	SW
0:00	26.8	0.8	26.1	1.3	27.0	1.1	26.1	1.4	---
6:00	26.9	0.1	26.7	0.6	27.1	0.0	26.7	0.6	---
12:00	26.8	-0.1	25.0	-1.6	26.7	-0.3	25.4	-1.3	SSW
18:00	26.8	0.0	25.9	0.8	26.8	0.0	25.9	0.	E
0:00	27.5	0.6	27.4	1.5	27.7	0.9	27.8	1.8	ENE
6:00	27.4	-0.1	28.0	0.5	27.5	-0.2	28.1	0.3	---

- **Fluctuation in Relative Humidity (%) with action Exp. NV + SS RBB in East-Oriented Living. & West- Oriented Bedroom. in March 2024**

Table 87: Comparison between Ext. RH (%) with base line reference (Δ RH $^{Room}_{air,REF}$) & Experiment (Δ RH $^{Room}_{air,EXP}$) with Action NV+SS:RBB for East-Oriented Living & West- Oriented Bedroom at 6 hour interval in March (cf. section 3.6.1, Eq 6 & Eq.7)

Time (t) Hrs.	**Relative Humidity (%) 15 & 16 MAR 24**	RH Fluc. in 6 Hrs.	**Ref. Liv. (RH) 13 & 14 Mar. 24**	RH Fluc. in 6 Hrs.	**Exp. Liv. (RH) 15 & 16 Mar. 24**	RH Fluc. in 6 Hrs.	**Ref. BRm. (RH) 13 & 14 Mar. 24**	RH Fluc. in 6 Hrs.	**Exp.BRm. (RH) 15 & 16 Mar. 24**	RH Fluc. in 6 Hrs.
6:00	75	0	56	0	56	0	65	0	65	0
12:00	20	-55	57	1	55	-1	67	1	64	-1
18:00	28	8	57	0	55	0	67	0	66	2
0:00	54	26	55	-2	55	0	64	-4	65	-1
6:00	63	9	57	2	55	0	66	2	65	0
12:00	26	-37	57	0	52	-3	67	2	61	-4
18:00	36	10	56	-1	52	0	66	-1	61	0
0:00	47	11	56	0	52	0	65	-2	59	-2
6:00	53	6	56	0	53	1	65	0	62	3

RÉSUMÉ

Architecture bioclimatique et climat chaud extrême - développements et expérimentations de stratégies actives et passives

Cette étude examine le potentiel de l'architecture bioclimatique dans les climats extrêmement chauds, en se concentrant sur le prototype BaityKool développé pour le Solar Decathlon Middle East 2018. Conçu pour s'adapter à l'environnement de Dubaï, ce prototype fonctionne désormais comme un laboratoire vivant, testant des stratégies de conception éco-responsables avec des systèmes passifs et actifs pour atteindre le confort thermique et réduire la consommation d'énergie. Des expériences ont été menées sur différentes saisons afin d'évaluer des stratégies telles que la protection solaire, la ventilation naturelle, leur combinaison et l'ombrage des terrasses. Ces expériences ont visé à démontrer comment la baisse de la température intérieure peut diminuer la demande énergétique pour le refroidissement et améliorer le confort des occupants. En été, trois types de rideaux dynamiques ont été installés sur les fenêtres et portes vitrées orientées à l'est et à l'ouest afin de réduire les apports solaires. Les tests de ventilation naturelle ont permis d'évaluer le potentiel de refroidissement gratuit grâce à la circulation d'air diurne et nocturne en hiver et pendant les saisons de transition (été-hiver et hiver-été). La combinaison de la protection solaire et de la ventilation nocturne vise à améliorer le confort thermique intérieur des occupants pendant les périodes de transition en bloquant le rayonnement solaire pendant la journée et en dissipant la chaleur la nuit. Le patio intérieur, avec son agencement et son orientation stratégiques, sa végétation et sa pergola solaire, a été évalué pour déterminer sa performance, notamment en tant qu'habitat bioclimatique. Enfin, la performance du système d'enveloppe sans rideaux d'ombrage a été évaluée afin de déterminer sa capacité à abaisser la température intérieure par rapport à la température extérieure, réduisant ainsi les fluctuations de température par des moyens passifs.

L'étude a visé : (i) à explorer le potentiel de l'architecture bioclimatique dans les climats extrêmement chauds, (ii) à évaluer les avantages de ces approches et (iii) à évaluer la faisabilité d'atteindre le confort thermique des occupants grâce à une combinaison de stratégies passives et actives, afin de réduire la demande énergétique pour le refroidissement dans différents scénarios.

Mots-clés : Architecture bioclimatique, climat extrêmement chaud, expérimentations, stratégie passive et active, confort thermique.

ABSTRACT

Bioclimatic Architecture and Extreme Hot Climates – Developments and Experimentation of Active and Passive Strategies

This study investigates the potential of bioclimatic architecture in extremely hot climates, focusing on the BaityKool prototype developed for the Solar Decathlon Middle East 2018. Designed to adapt to the environmental conditions of Dubai, this prototype now serves as a living laboratory for testing eco-responsible design strategies integrating passive and active systems to achieve thermal comfort while reducing energy consumption. Experimental campaigns were conducted across different seasons to evaluate strategies such as solar protection, natural ventilation, their combination, and terrace shading. These experiments aimed to demonstrate how lowering indoor temperatures can reduce cooling energy demand and improve occupant comfort.

During summer, three types of dynamic shading curtains were installed on east- and west-facing glazed openings to reduce solar gains. Natural ventilation tests assessed the potential for free cooling through daytime and nighttime airflow during winter and transitional seasons (summer-winter and winter-summer). The combination of solar protection and night ventilation aimed to enhance indoor thermal comfort during transition periods by blocking solar radiation during the day and dissipating heat at night. The inner courtyard characterized by its strategic layout and orientation, vegetation, and solar pergola was evaluated to determine its performance, particularly as a bioclimatic habitat. Finally, the performance of the envelope system without shading curtains was assessed to determine its ability to lower indoor temperature relative to outdoor conditions, thereby reducing temperature fluctuations through passive means.

The objectives of this study were: (i) to explore the potential of bioclimatic architecture in extremely hot climates, (ii) to assess the benefits of these approaches, and (iii) to evaluate the feasibility of achieving occupant thermal comfort through a combination of passive and active strategies, in order to reduce cooling energy demand under various scenarios.

Keywords: Bioclimatic architecture, extreme hot climate, experimental study, passive and active strategies, thermal comfort

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