PASSIVE DESIGN STRATEGIES FOR ZERO ENERGY HOUSES IN DESERT ENVIRONMENTS: THE CASE OF SOLAR DECATHLON MIDDLE EAST 2021

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ABSTRACT

The high energy consumption of buildings in desert environments, caused mainly by high cooling needs, calls for mitigation. In Dubai, it is estimated that buildings account for 70% of the total energy demand, and this share is expected to grow due to the urbanization rate. One strategy to reduce building consumption is implementing zero energy buildings. These are energy-efficient buildings capable of generating their own energy consumption. Passive design options are key for managing building energy demand. This work analyses the passive design options used in zero energy houses in Dubai for the Solar Decathlon Middle East 2021, where the participating teams designed, constructed, and test-operated fully solar-powered houses. First, we describe the strategies that include compactness of the building shape, orientation, and the envelope's thermal performance, and compare them with the best practices for the region. We find that the high-performing opaque surfaces exceed Dubai's Green Building Rating system, the transparent surfaces are mostly placed in the north unshaded, the east and west facades have little to no openings, while the south ones are mostly horizontally shaded, and there is a low window to wall ratio. Lastly, we consider the effect of these strategies against the monitored building performance during the competition: the light level (lux), the electricity consumed for heating, cooling, ventilation, and lighting (kWh), the indoor temperature (°C), controlling for solar radiation (W/m^2) and outdoor temperature. The findings highlight solutions that best respond to Dubai's environment and help to improve the energy performance of the buildings in desert climates.

Keywords: zero energy buildings, passive design strategies, desert environment, solar decathlon.

1 INTRODUCTION

The Dubai Clean Energy Strategy has a goal of 25% of Dubai's electricity from clean energy by 2030 and 75% by 2050 [1], and the UAE Net Zero by 2050 strategic initiative's goal aims to achieve net-zero emissions by 2050 [2]. Historically, policies have introduced targets and standards to promote more efficient use of energy, generating significant savings in buildings. One key strategy aimed at lowering building energy demand has been the introduction of zero energy buildings (ZEB) as an aspirational target for new buildings, as well as for existing buildings [3]. Zero energy buildings are buildings with significantly reduced energy demands by energy-efficient design so that the balance of the energy demand can be supplied by renewable energy that is mostly generated onsite [4].

To achieve low energy demand, designers can utilize active and passive options. A significant portion of the building's energy consumption is influenced by the climate of the building's location. Active options aim on providing building services like lighting, air conditioning, and appliances with the highest feasible efficiency. Passive design strategies can help reduce the need for HVAC to keep the same indoor comfort levels [5].

Solar Decathlon Middle East (SDME) is a competition developed by the collaboration of the Dubai Supreme Council of Energy, Dubai Electricity and Water Authority (DEWA), and the US Department of Energy, that challenges university students to design, build and operate for two weeks fully powered solar energy houses. The results are a live demonstration of innovations in design, materials, and technology developed for zero energy buildings (ZEBs)

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in the region. Because the rules of the competition constrain the participants equally, SDME gives a chance to study real building energy performance in a controlled environment [6].

Our paper provides an overview of the main passive design strategies that can help achieve ZEBs in desert environments by analysing the houses of the 2021 Solar Decathlon Middle East (SDME) competition. Buildings in Dubai can benefit highly from passive design strategies. Section 1.1 describes what passive design is and presents its main applied strategies. In Section 1.2 Dubai's annual and seasonal climate conditions are presented, followed by Dubai's building requirements for passive design in Section 1.3. The methodology of the work is presented in Section 2, followed by the analysis of the SDME 2021 houses' passive design strategies in Section 3. Finally, conclusions are presented in Section 4.

1.1 Passive design strategies

Passive design strategies are utilizing natural resources to maintain hygrothermal comfort by optimizing direct and indirect heat gains. These strategies work with no fuel or electricity input and need minimum maintenance. The main passive designs apply to the geometrical parameters and ratios, building envelope, building orientation, and any properties that determine heat gain, and heat loss in buildings [5].

The geometrical parameters and ratios determine the exchange interior–exterior surface area, while the orientation determines the areas exposed to direct or indirect radiation [5]. Envelope to building volume ratio needs to be minimized to improve energy conservation, because a high value leads to higher heat gains [7], similar to window to wall ratio (WW) the higher the glazing area the higher the potential for solar gains [7]. Where two materials with different thermal conductivities meet, creating an interruption of the uniform thermal insulation layer, thermal bridges are created [8], and in order to avoid heat gains they need to be minimized. In terms of orientation, for hot climates in the northern hemisphere, the preferred option for energy efficiency is to minimize the facades in the west and east, while shading the south façade [7].

The selection of material and design of building thermal envelope is one of the most effective ways to minimize its energy consumption, especially in extreme climates. The thermal envelope comprises of opaque and translucent surfaces that separate the conditioned areas from the unconditioned ones, and it controls the heat exchange between the flows building interior and exterior. Proper design of the roofs, walls, floors, and fenestrations takes advantage of the favourable exterior conditions and blocks unfavourable ones [5].

Shading can be fixed or moveable, vertical, in parallel to the glazing, or horizontal, perpendicular to the glazing. In terms of building use, commercial buildings show more energy savings from having shading to the glazing, one of the reasons being that commercial buildings have larger glazing areas than residential buildings. Similarly, green walls and roofs lower energy loads because they bring evaporative cooling to the outer surface of the building. Vegetation also increases the air quality as well as adds acoustic insulation. On the other hand, vegetation increases the maintenance cost, as well as the water consumption [7].

1.2 Annual and seasonal climate conditions

Dubai has a subtropical desert climate with high solar radiation all year round, and two seasons, winter, and summer. Summer, the longer season, has hot temperatures from April to November, although the proximity to the sea influences its temperatures, making them milder compared to neighbouring inland locations. Proximity to the sea increases humidity levels, impacting outdoor comfort during the summer months.

During the competition period, 13–24 November 2021, the weather was mild, a period considered to be the beginning of winter in Dubai. The temperature varied from 15°C to 34°C, with humidity that varied from 10% to 85%, and a wind speed lower than 9 m/s.

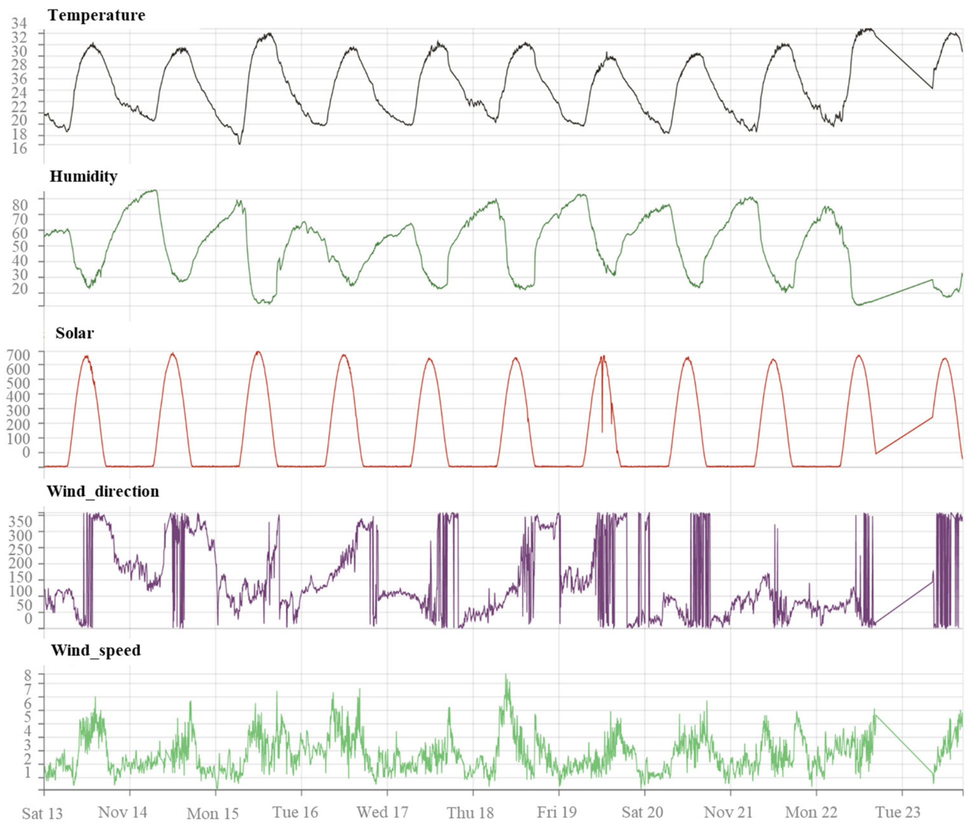

Figure 1: Weather data during the complete contest duration: temperature (°C); humidity (%); solar radiation (W/m^2); wind direction (°) – north; and wind speed (m/s) [6].

1.3 Dubai building requirements for passive design strategies

Dubai's Green Building Rating System is called Al Sa'fat [9], and its goal is to lower buildings' energy consumption, and improve the efficiency of their electrical and mechanical systems. Al Sa'fat has three certification levels: silver, the base level, mandatory for all new buildings and facilities in Dubai since 2020, gold, and platinum. There are 33 mandatory general requirements and many optional provisions, determining the building certification level. In terms of passive design strategies, Al Sa'fat includes requirements for microclimate and outdoor comfort, occupant comfort, daylight and thermal, for building envelope performance, air leakage, and shade effect.

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Al Sa'fat sets minimum performance requirements for all new air-conditioned buildings. For opaque envelope elements, the average thermal transmittance, U-value, for the roof has to be lower or equal to 0.3 W/m^{2}K for all levels of Al Sa'fat, while, for external walls and exposed floors to the exterior, it has to be lower or equal to 0.57 W/m^{2}K for Silver Sa'fat and 0.42 W/m^{2}K for Golden and Platinum Sa'fat, values summarized in Table 1. Silver Sa'fat requires that the orientation of the glazed facades is more than 50% of the building's total glazed area is facing an angle of 135° starting from east to north. In comparison, the Golden and Platinum Sa'fat requires both requirements to be fulfilled. For glazed envelope elements, the minimum performance requirements vary based on whether the window to external wall ratio is less than 40%, in between 40% and 60%, or greater than 60%. The requirement values thermal transmittance (U-value), shading coefficient (SC), and light transmittance are summarized in Table 1.

Table 1: Al Sa'fat 2020, performance criteria for opaque envelope and transparent envelope.

Opaque envelope	Silver Sa'fat			Golden and Platinum Sa'fat		
Max U-value roof	0.3 W/m^{2}K			0.3 W/m^{2}K		
Max U-value Walls, floor	0.57 W/m^{2}K			0.42 W/m^{2K}		
Transparent envelope	Silver Sa'fat			Golden and Platinum Sa'fat		
	WW< 40%	40%<WW<60%	60%<WW	WW<40%	40%<WW<60%	60%<WW
Max U-value	2.1 W/m^{2}K	1.9 W/m^{2}K	1.9 W/m^{2}K	1.9 W/m^{2}K	1.9 W/m^{2}K	1.7 W/m^{2}K
Max SC	0.4	0.32	0.25	0.32	0.25	0.25
Min visual transmittance	0.25	0.1	0.1	0.25	0.1	0.1

Lastly, Al Sa'fat addresses thermal bridges, air loss from entrance and exits, air leakage, and shade effect calculations. Thermal bridges should be reduced and efficiently insulated to reduce the amount of heat transfer. The air loss from the regularly used entrance and exits in air-conditioned buildings has to be mitigated with efficient barrier systems. When it comes to the shade effect calculations, the impact of external shade factors on the building's thermal load must be calculated for all new buildings other than villas, but there are no numerical required value limitations.

2 METHODOLOGY

To identify the most effective strategies, we characterize the main passive strategies according to the following characteristics: compactness of the building shape, orientation, and the envelope's thermal performance, followed by a comparison of these strategies and of what is considered to be the best practices for the region. These strategies are compared with the monitored building performance during the competition, in (kWh) and (kWh/m^2) for the HVAC and total electricity consumption, as well as the interior lighting level, temperature, and humidity, considering the exterior temperature and humidity levels.

All the houses presented in the SDME competition are considered for this study. Abbreviations are used for the houses, and they are listed in alphabetic order. The data sources for the study include: the in-person assessments during the competition, reports, modules, and drawings submitted by the teams; and data collected from measurements during the competition.

A review was carried out based on the information available from the organizers, the project manuals, reports, and drawings, as well as from in-person visits on-site during the competition.

3 ANALYSIS

Eight houses participated in the SDME 2021, pictures shown in Fig. 2, from various universities, listed here in alphabetic order: BUD, from The British University in Dubai, UAE; HWU, from Heriot-Watt University, UK and UAE; KFU, from Khalifa University, UAE; MPU, from Manipal Academy of Higher Education, UAE; SCU, from South China University of Technology, China; UOB, from University of Bahrain, Bahrain; UOL, from University of Louisville, American University in Dubai, American University in Sharjah, Higher Colleges of Technology, USA, and UAE; UOS from University of Sharjah, UAE.

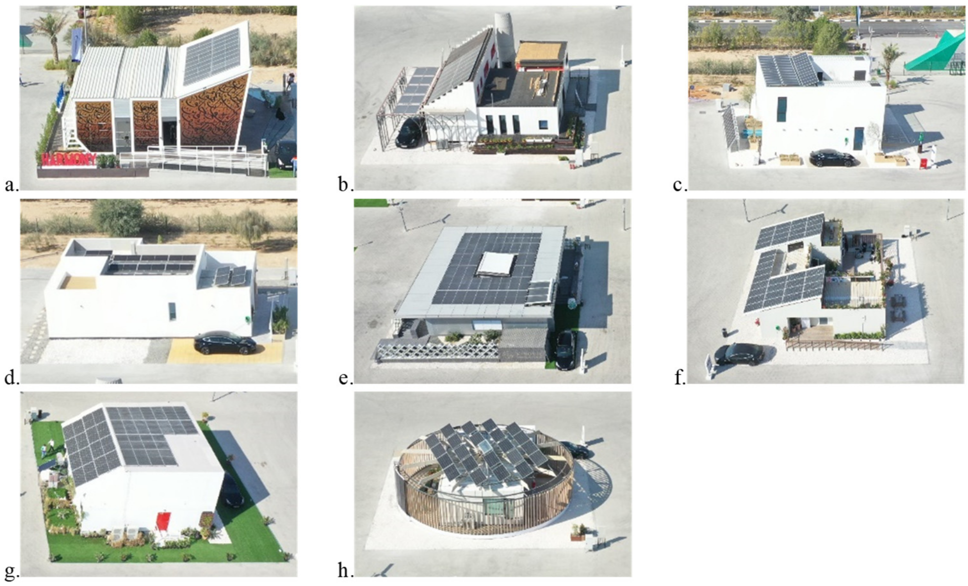

Figure 2: Aerial images of the SDME 2021 houses. (a) BUD; (b) HWU; (c) KFU; (d) MPU; (e) SCU; (f) UOB; (g) UOL; and (h) UOS.

3.1 Geometric properties

Most of the buildings have a rectangular shape, regular or with some variations, as can be seen from their plans in Fig. 3. UOS and UOL have rectangular shapes, while UOB has an almost square shape. HWU and SCU also have almost square shapes but with variations added by courtyards, which for HWU is on the west side, creating almost u-shape of the house, while for SCU is in the canter. KFU is also in between a square and a u-shape, where each floor is a u-shape but with opposite directions and placed on top of each other create a square footprint of the house. UOB has the most distinct u-shaped plan. And lastly, MPU has a plan formed by two shifted rectangles. None of the houses has a curved plan shape. UOS can give the impression that the facades are curved by the surrounding fence around the rectangular plane. The reason for this choice can be the optimization of utilizing the site's shape and, at the same time to simplify construction. In terms of passive design strategies, this shape works very well, and the almost dominant almost squared plans work well as the most compact the shape, the better it keeps the heat gains out.

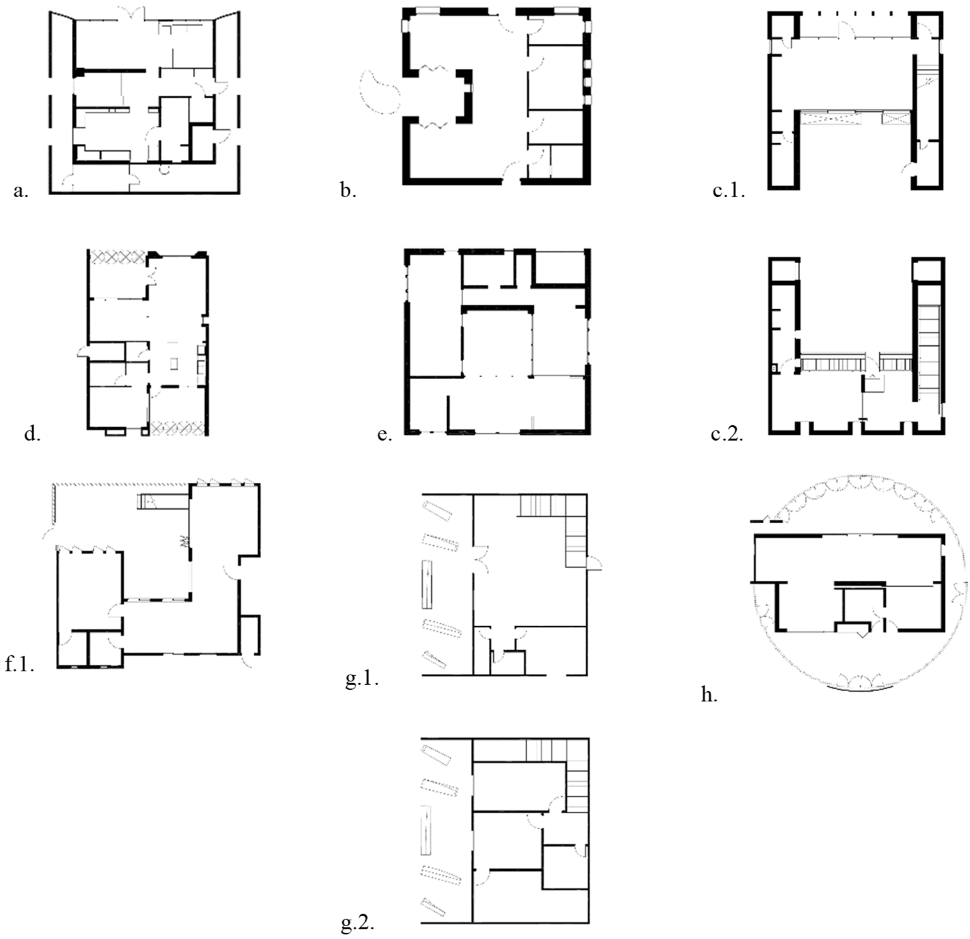

Figure 3: Plans of the SDME 2021 houses. (a) BUD ground floor; (b) HWU ground floor; (c.1) KFU ground floor; (c.2) KFU first floor; (d) MPU ground floor; (e) SCU ground floor; (f) UOB ground floor; (g.1) UOL ground floor; (g.2) UOL first floor; and (h) UOS ground floor.

Table 2 gives a summary of the ratio of the window areas compared to the total wall area (WW) for the SDME 2021 houses. This ratio varies from 0% up to 56%. The total average WW is 17%. In addition, it is crucial to report the orientation of these glazed areas. Most of the openings are in the northern façade. Considering the Dubai climate, this is the best orientation for the glazed areas since it allows to have daylight while minimizing the heat gains compared to the other orientations. The south and west have almost similar ratios to each other that are almost 50% lower than the openings on the northern facade. The south façade is the one that has the most heat gains but glazing here is easy to be shaded from horizontal shading elements, while the north can be shaded by vertical shading elements. The east has the lowest amount of opening because it is difficult to shade due to the angle of the rays in summer.

Table 2: Window to wall (WW) ratios.

	BUD	HWU	KFU	MPU	SCU	UOB	UOL	UOS
WW North	56%	22%	48%	38%	42%	27%	2%	28%
WW East	0%	9%	7%	7%	15%	4%	0%	19%
WW South	8%	16%	38%	8%	17%	10%	2%	16%
WW West	12%	4%	3.5%	0%	28%	22%	5%	28%
WW Total	20%	14%	23%	11%	25%	15%	3%	22%

Note: Information provided by the participating teams.

3.2 Building orientation

The orientations of the buildings are more along the axis north–south, the reason for this being to maximize the northern façade that has the lowest heat gains and to minimize facades in the east and west that are more difficult to shade than the south. The orientation of the building entrances is from the north, HWU, KFU, and BUD. This is considered a good choice because the entrance in the north means that every time the door is open, the heat gains will be less on this orientation. Most of the entrances are directly into the living room, and few of them are from foyers that are separated from the living room, which creates a buffer zone but is not fully closed. The orientation of the main zones, mostly the living rooms, are oriented in the north, while the east and west are preferred for services. In terms of courtyard orientations, different approaches were applied. UOB and UOS have their courtyards placed on the north, MPU has two courtyards, both on the north and on the south where the southern one is shaded, KU has its courtyard on the south but fully shaded, HW in the west, and lastly, SCU has placed the courtyard in the centre. Teams opted for light material to lay the courtyard ground, such as white gravel is white that helps with the cooling.

3.3 Building envelope

Table 3 summarizes the thermal transmittances for both the opaque and the transparent envelope. Most of the values are as required by Al Sa'fat gold and Platinum for opaque, with the exception of one of the HWU walls and UOB floor, and the same is true for the glazed areas. In terms of insulation, Rockwool is the most common material, but other materials such as Phenolic insulation are used as well.

Table 3: Building envelope thermal transmittance (U-values).

U-value (W/m^2K)	BUD	HWU	KFU	MPU	SCU	UOB	UOL	UOS
Walls	0.24	0.17–0.7	0.15	/	0.14	0.26	/	0.26
Floor	0.22/0.42	0.1–0.22	0.22–1.77	/	/		/	0.2
Roof	0.18	0.1	0.1	/	0.14	0.32	/	0.24
Windows	1.3	0.96	1.3–1.5	/	1.79	1.52–1.75	/	

Note: Information provided by the participating teams.

Some of the other passive design strategies are ventilated façade, applied by UOS and SCU, as well as double-shell façade applied by BUD wind circulation and shading. Another strategy is to use plants for shading the opaque and mostly the glazed envelopes. A unique solution was applied by MPU, inspired by traditional Islamic architecture, mashrabia, which is a type of oriel window enclosed in carved wooden panel [10]. The mashrabia doors limit

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the courtyards that constantly revolve from the wind creating a cooling effect. Lastly, HW applied a wind catcher inspired by the UAE vernacular architecture, which is designed to capture the cooler air at the top and draw it down to cool the house's courtyard area.

3.4 Two detailed case studies, SCU and KU

A more detailed description of two of the houses is presented here, SCU and KU, in order to give a better understanding of the design strategies are combined together in one house.

The SCU house, Fig. 4 has a closed appearance to the outside, and it opens towards the inner courtyard, a choice influenced by the harsh weather, to create a temperature buffer, and shield the house from any potential sandstorm, and also influenced by the local cultural inclination towards more privacy. The inner courtyard, shaded by the house walls on all four sides, allows for daylight to enter the house while it significantly lowers the temperature. The roof of the SCU house is composed of two layers. The upper layer is where the photovoltaic modules are placed, avoiding direct contact with the lower roof, reducing this way the heat gains from them. In addition to this, the upper layer of the roof creates a shade on the house, wider in the south. It has been designed that in the hot summer month, the shade covers all the southern façade, limiting this way the heat gains. The space between the two layers of the roof has shutters and plates that move according to the weather, which opens, and closes based on the need for shield or ventilation, but they are active, not passive, and the same is true for the courtyard that can be fully covered or opened based on the weather. The cover is active but sliding doors surrounding the atrium to open or fully close the space are part of the passive strategies.

Figure 4: Aerial images of the SCU house.

Figure 5: Aerial images of the KU house.

In terms of the opaque envelope, the SCU house has a steel structure, while the walls are composed of plywood finish, moisture-proof membrane, sound insulation board, phenolic insulation, sound insulation board, waterproof membrane, vacuum insulation panel, finish keel, ceep aluminum finish. Phenolic insulation is placed in between the wood keels, and vacuum insulation plates are placed on top that has a 0.002W/mK conductivity. In order to prevent thermal bridges, wood keel is used instead of steel keel, a material with lower thermal conductivity, vacuum insulation panels are placed on the outer walls, and aerogel insulation is used to attach the parts that might create thermal bridges. In terms of the glazed envelope, triple glazing with double Low-E coating and double vacuum layers. The U values are lower than 0.79 W/m^{2}K for all the glazing except the folding doors in the atrium, which are double glass, with an aluminum frame and a U value lower than 1.3. The skylight is also double glass with three layers of Low-E coating, while the frame is a combination of glass fiber and polyurethane. All the glazing has external shading, which is automatic, not passive.

The KU, Fig. 5, has a different layout of the hose to optimize for the passive design. The ground floor is connected to the southern garden, planed for indoor–outdoor living. The garden is fully shaded by the upper floor, and its design is to be perceived as an extension of the living room. The west and east sides of the house are planned as buffer zones, placing there the service areas, where the washing room and MEP room, are placed in the west, while the powder room, battery room, and stairs to the upper floor are placed in the east. The bedroom, study, and bathroom are placed on the first floor facing north into the roof garden, which is designed to create a privacy buffer for the indoor areas while at the same time creating the indoor–outdoor living perception.

In terms of the building envelope, the external walls of the KU house are made of cementitious boards, Knauf Aquapanel, painted off-white. The roof has a Kingspan KSD10000 sandwich system, while the floor has natural stone. The KU house has large, electrochromic glazed areas in the north, a hybrid passive solution, large, glazed areas in the south ground floor fully shaded by the upper floor, and narrow windows, on the south of the upper floor, placed on the inner side of the walls for shelf shade. The placement of the windows in the north and south also helps to create cross-ventilation from north to south.

The KU house used the green areas as passive design strategies, where the garden on the roof of the ground floor reduces the solar gains because the soil and the vegetation act as thermal masses to reduce heat gains. In all the green spaces, local, low irrigation demand plants are used, such as the Ghaf Tree (*Prosopis Cineraria*) and the Gum Tree that is pleasant and provides shading and buffer.

3.5 Building energy performance

The light level, the indoor temperature, and particularly the electricity consumed for heating, cooling, ventilation, and lighting are significantly affected by passive design strategies. Relying solely on this metric of performance may not be fully representative for several reasons. First, these performance metrics are significantly affected by the active systems, their efficiency, and their efficacity to keep the internal comfort level. In addition to this, the occupant behaviour, such as using the window shades, opening, and closing the doors, significantly affects the utilization of the passive design technique.

Also, the performance of the houses does not reflect well the designed strategies is the construction quality and execution of the design. For instance, although both the SCU and the KU houses utilize well passive design strategies and maintained the same temperature of 20°C minimum and 31°C maximum in the living room, and of 19°C minimum and 30°C maximum in the bedroom, during the competition as seen in Fig. 7, the energy consumption of the KU house is significantly higher than that of the SCU house. At the end of the competition, KU had cumulative consumption of electricity for heating, cooling, ventilation, and lighting higher than 400 kWh, one of the highest among all houses, while SCU kept it lower than 150 kWh, the lowest of all the houses, as seen in Fig. 6.

One of the main reasons that the KU house performed not as well as it was predicted to is due to the occupant behaviour during the competition, and due to the execution of the design, for example, the airtightness of the house was not well executed, while the SCU house had both the construction and the occupant behaviour optimized.

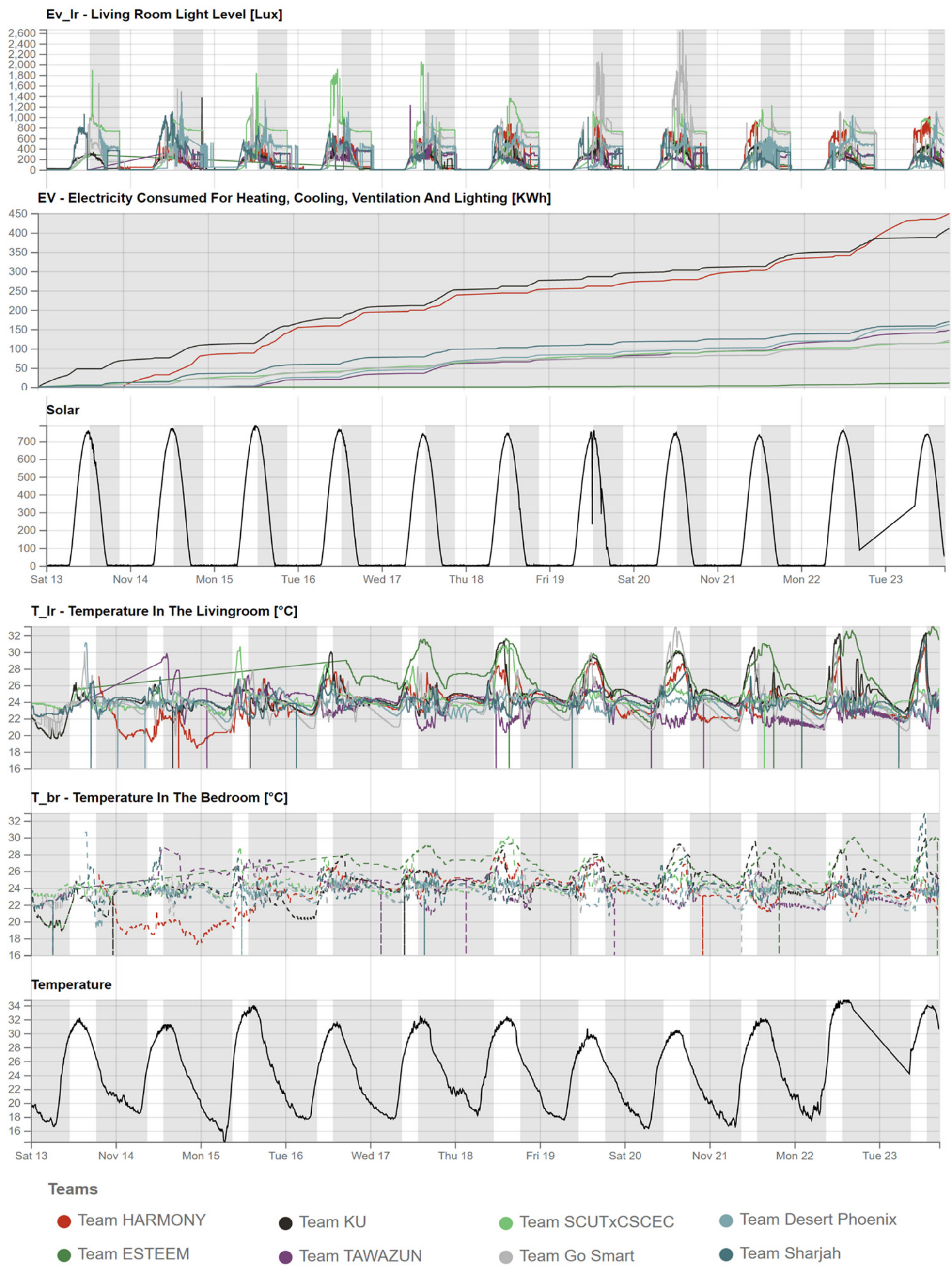

Figure 6: Living room light level (lux); electricity consumed for heating, cooling, ventilation, and lighting (kWh); outdoor solar radiation (W/m^2); living room temperature (°C); bedroom temperature (°C); and outdoor temperature (°C); during the contest duration, for all eight teams [6].

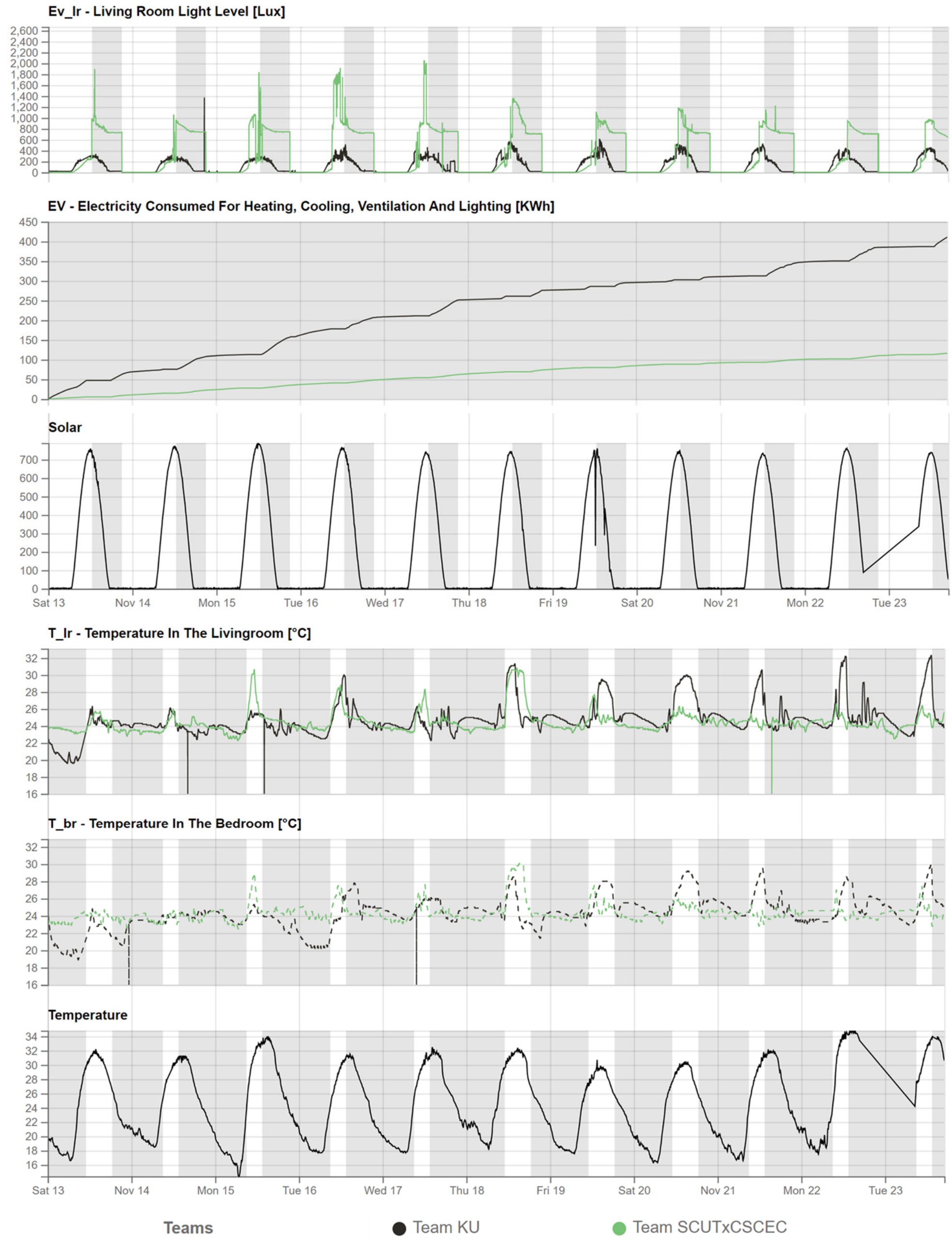

Figure 7: Living room light level (lux); electricity consumed for heating, cooling, ventilation, and lighting (kWh); outdoor solar radiation (W/m^2); living room temperature (°C); bedroom temperature (°C); and outdoor temperature (°C); during the contest duration, for all eight teams [6].

3.6 Lessons learned p

This study provided an overview of the passive design strategies used in the 2021 SDME houses. Lessons that can be learned and recommendations are as follow:

- When it comes to geometrical parameters, given Dubai's hot and humid climate buildings have a high cooling demand, compact building form factors perform better because of the minimization of the exchange surface of the building conditioned volume with the outside.
- In terms of orientation, given that Dubai is in the northern hemisphere, the north façade receives less direct radiation, while the south facades receive higher solar angles, which can be easily protected by adding horizontal shading elements.
- In the east and west, the solar angles are low, which makes it challenging to protect the facades with fixed shading elements. Based on these facts, the better orientation for buildings in Dubai is to have the longest facades towards the south and north, meaning having an east–west axis. For the same reasons, to optimize the building energy performance, the better orientation for the glazing surfaces in Dubai buildings is the north, which receives less direct solar radiation, followed by the south, which can be easily shaded because the solar angles are high. At the same time, the glazing areas in the east and west should be minimized as much as possible.
- In terms of the distribution of the interior spaces, using service spaces such as staircases, elevator shafts, storage, and mechanical rooms in the west reduces the effect of the exterior temperature and solar radiation. Bathrooms, toilets, closets, and other spaces that can be affected by the humidity in the west or south-west façade to help reduce the impact of the exterior environment and minimize the adverse effects of the moisture in these spaces.
- In terms of building thermal envelope, a high-performing building thermal envelope is one of the most effective ways to minimize building energy consumption, and this is especially relevant in extreme climates such as Dubai. The thermal building envelope is compromised by the opaque elements, such as walls, roofs, and floors, and it is compromised by the transparent elements such as windows and other glazed surfaces. Proper design of these elements means taking advantage of the favourable exterior conditions such as daylight and fresh air and blocking the unfavourable ones such as heat gains.
- Lastly, based on this work, it can be learned that even in the cases of good passive design strategies, the execution of the design in the construction phase and the occupant behaviour after the construction phase significantly affects the performance of the design.

4 CONCLUSION

Passive design strategies significantly influence the energy performance of the houses. This means that they have a significant influence when it comes to achieving ZEBs. In this work, passive design strategies of Solar Decathlon Middle East (SDME) 2021 houses were analysed, including geometric properties, orientation, and building envelope. After a description of these strategies, a discussion was done on how they affected the performance of the houses in response to Dubai's context.

SDME is an international competition where students design, construct and operate zero energy buildings (ZEBs). The participating houses used several passive design strategies, a good combination between strategies such as geometric parameters, orientation, and envelope, which helped to maintain the house's interior comfort levels and reduce the need for active systems. Through these works, it can be concluded that the houses had a good potential to be zero energy buildings all year long.

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