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A review of passive envelope measures for improved building energy efficiency in the UAE

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Abstract

The United Arab Emirates' (UAE) hot climate, coupled with the extreme demographic and urban growth experienced over the past four decades, has shaped a built environment where energetic quality of construction has been superseded by the quantity of construction needed to support the country's growth. This development is further aggravated by the slow development of energetic building codes, as well as the subsidized cost of electricity. The result is that the UAE consistently leads the list of countries with the highest environmental footprint, and the electricity production required to drive building cooling constitutes the brunt of the emissions balance-sheet. The work presented here reviews primarily UAE-based research that addresses the effectiveness of passive building-envelope measures that reduce energy consumption. A number of measures have been developed in response to the increasing demands of emerging energy regulations, and include measures specific to the building envelope in the planning phase or as retrofit, including radiative, convective and conductive heat transfer through walls, windows, roof, as well as energy efficient natural ventilation techniques. This review is geographically restricted to the UAE as its development challenges are directly tied to its distinct economic growth pattern and specific legislation implemented to address energy efficiency. Results confirm the importance of the following factors for energy-optimized structures: building orientation, thermal insulation (which can generate in excess of 20% energy savings in particular in the residential context), appropriate glazing type and orientation in highly glazed office buildings (up to 55% energy savings reported), excessive light levels and glare, and natural ventilation, which can reduce energy consumption from a reported high of 30% in villas to up to 79% in a high rise office building using mixed mode ventilation.

Keywords: UAE; Energy efficiency; Building envelope; Wall insulation; Windows; Natural ventilation

Abbreviations:

HVAC	Heating, Ventilation and Air Conditioning
GDP	Gross Domestic Product
DPW	Department of Public Works
USGBC	US Green Building Council
LEED	Leadership in Energy and Environmental Design
U-value	Heat transmittance through a building component (W/m^2K)
EPS	Expanded Polystyrene
AAC	Autoclaved Aerated Concrete
EUI	Energy Utilization Intensity (kWh/m^2 a)
SHGC	Solar Heat Gain Coefficient
GHG	Greenhouse Gas
CAV	Constant Air Volume

VAV Variable Air Volume

1. Introduction

The worldwide building sector consumed 32% of the global final energy in 2010, and was responsible for one-third of global CO_2 emissions [1]. Building energy consumption is particularly pronounced in extreme climates, where indoor space conditioning constitutes the largest portion of a building's energy needs. In both cold and hot climates, active systems have to either heat or cool the building to maintain occupant comfort. Further, humidity levels must be kept at acceptable levels, and sufficient fresh air has to be delivered to ensure a healthy environment for occupants. Thus a building's energy consumption is governed by climatological factors, technical factors (energetic quality of the building's envelope and space conditioning), and occupant behavior [2].

In cold climates most energy is consumed by on-site burning of biomass and fossil fuels to generate heat, while in hot climates the space conditioning systems typically rely on electricity as energy source. Energy efficiency strategies however are similar, as heat is lost or gained through the building envelope. Conduction losses through the wall and windows are mitigated in both cases by decreasing the enclosure's U value. Radiative losses or gains however receive a different treatment, as in cold climates they are desirable to reduce heating load, whereas in hot climates they increase the cooling load. Thus in climates like the UAE, window treatments in the form of selective coatings and the appropriate design of shading elements become critical fenestration components. In both cases, and in order to minimize energy consumption, it is important to first optimize the envelope and then address the active heating or cooling systems, as these can consequently be sized for a smaller load.

On the long term, and taking into consideration climate change, worldwide heating energy demand is projected to decrease by 34% by the year 2100, while cooling demand is estimated to increase by 72% over the same time period [3]. Thus the already severe cooling need of buildings in arid regions is projected to increase over the next century, further impacting the often poor energetic and sustainability balance sheet of these regions, and underscoring the necessity of energy efficiency measures.

The UAE's extreme climate generates a challenging environment for energy conservation and environmental sustainability of buildings [4]. The temperature (wet bulb design temperature of 30.6°C and dry bulb design temperature of 45.0°C [5]) and humidity (80% in winter and 70% in summer [5]), combined with the high solar irradiance (yearly average global horizontal irradiance in excess of 20 MJ/m2/day [6])**,** make air conditioning a necessity to maintain acceptable indoor comfort levels. The resulting electric load attributable to HVAC equipment accounts for 40% of the total year average electrical load, and up to 60% of the summer peak load [7]**.**

The challenges that arise due to these extreme climatic conditions are further compounded by the exponential growth of the country since its formation as a federation of seven Emirates in 1971. The UAE's Gross Domestic Product (GDP) has risen at an average rate of 4.9% annually from 30 Billion $US in 1980 to 81 Billion $US in 2003, and the resulting population growth spans from an estimated 0.7 million inhabitants in 1980, to 3.25 million in 2003 to 9.157 million in 2015 [8,9]. This rapid growth, primarily caused by the economic development due to oil sales and the ongoing repositioning of the country as a commerce and high-tech hub, has triggered a continuous influx of foreign workers and businesses. The infrastructure and urban development to support this growth has had to assume unprecedented scale.

Looking at the example of the Emirate of Dubai, first available statistics from 1955 show an urban area of only 3.2 km^2 in 1955, which grew to 606 km^2 in 2004, with further plans to extend the built-up area by another 501 km^2 by 2015 [10]. The urban development has adopted a cluster approach, with numerous mixed-use and residential clusters. In addition to housing developed for UAE nationals provided by the Department of Public Works (DPW), the clusters are typically developed by one of the major real estate developers, and sold as investment property or for personal use. Bagaeen [11] argues that the opening of the real estate market to the exterior, by allowing foreigners to buy freehold property in Dubai, has been the catalyst of this rampant expansion. In order to maximize profits, the major developers pursue economies of scale, and it is not uncommon to have hundreds (if not thousands) of homes built simultaneously in newly developed areas. In accordance, the residential villa stock has grown by over 300% from 2000 until 2009 [12].

Fig. 1. Typical single-family villa development in Dubai.

The growth in energy demand follows suit: in 1995 the demand was 25 TWh, in 2003 50 TWh, and in 2007 76 TWh [7], of which (2005 data) 45.9% was attributable to residential buildings and only 2.5% to commercial buildings [13]. Mokri et al. [6] report an annual increase in electricity demand of 10.8%.

A key factor contributing to this very high energy demand growth rate is that the cost of energy is kept artificially low through government subsidies. While the cost of production of a kWh of electricity is estimated to be $0.12 to $0.13, it is sold at an average rate of $0.04 per kWh in Abu Dhabi (with a further reduction for UAE nationals), and at a slab rate ranging from $0.06 to $ 0.10 per kWh in Dubai [5]. In addition to these low prices (and notwithstanding increasing efforts by the government to counteract this), there is a general unawareness of environmental and energetic considerations in the population [8]. These factors contribute to an average per-capita energy consumption that is nine times higher than the world’s average energy consumption, four times higher than the EU’s energy consumption, and two times higher than the US energy consumption [8]. These factors make the UAE the country with the highest ecological footprint in the world [5].

Thus an environment inclined to poor energy efficiency is created by:

- The need for rapid construction to accommodate rapid population growth
- The large-developer business model, where profit is maximized while keeping initial construction costs low [14]
- The artificially low cost of energy, reducing the perceived importance of operational cooling costs during the lifetime of the building
- The long time absence of any energy regulation forcing the implementation of insulation and efficiency measures
- The general unawareness of environmental concerns by the population

The UAE government is actively pursuing renewable energy technologies with the aim of addressing worldwide concerns regarding global warming and greenhouse gas emissions, and at the same time preparing an economic pillar for the country's growth beyond the oil years [6]. However, while renewable production has received much attention, energy conservation through effective construction is only slowly becoming mainstream through the development and implementation of adequate legislation.

This paper provides a review of work done specifically in the UAE on improving building energy efficiency by passive measures implemented to the building envelope in the planning phase or as retrofit, including radiative, convective and conductive heat transfer through walls, windows, roof, as well as energy efficient natural ventilation techniques. The review is geographically restricted to the UAE as its specific development challenges are directly tied to the distinct economic growth pattern of the country and the specific legislation implemented to address energy efficiency.

2. Energy efficiency regulation

The UAE is a young country that has experienced meteoric growth over the past decades. Due to this rapid growth, environmental considerations have lagged behind development needs, and only recently regulations have been put in place that address sustainability and energy consumption in buildings. In 2003, the Dubai Municipality introduced the Decree 66, which provides directives on insulation and glazing and, in 2007, Abu Dhabi followed suit by establishing the Urban Planning council, which subsequently developed and launched the ESTIDAMA Pearl building rating system in 2010. Dubai then introduced the Green Building Regulation [15] in 2011, which was mandatory for all government buildings and optional for non-government buildings, and then extended it to mandatory for all newly constructed buildings in 2014. Sharjah has also had thermal insulation regulation in place since 2003, that specifies insulation characteristics of walls, roof and glazing. The other Emirates (Ras Al Khaimah, Ajman, Fujairah, and Umm al-Quwain) either do not have energetic regulations in place, or are in the process of developing them [13]. Regardless of these developments, the USGBC LEED certification is perceived as prestigious and still pursued regularly, although it is arguable whether the application of a cost-of-energy based rating system developed for the US market by the USGBC is appropriate in the specific UAE climatic and constructive environment [7, 16].

There is clearly a rapid progression of emerging building energy efficiency regulations being implemented in response to the frantic growth of the UAE. These regulations differ from Emirate to Emirate, and are slowly becoming mandatory, however their execution is only becoming enforceable as the development and certification of implementation professionals increases [17]. In addition, these regulations focus on new buildings, and do not consider that the large building stock constructed during the past four decades is not energy efficient [7]. In the absence of binding regulations, a large number of UAE buildings have been mass-built by the major developers for sale to the end customer, with clear emphasis on minimizing the cost of construction so as to maximize profit while disregarding the operational aspect of the building life, a cost that the end user will assume. This has resulted in an energetically deficient building stock. AlNaqbi et al. [7] report that 27% of the Dubai residential building stock and 12.8% of the Sharjah residential building stock were completed pre-2003, and thus did not include any requirement for insulation. Abu Dhabi did not have an insulation requirement before 2010, and thus over 290,000 residential units (not including units built by DPW for UAE nationals) built since 1975 [7] did not have to incorporate any level of building insulation. A sample computational case study to assess the potential saving generated by retrofitting the existing poorly insulated villa stock to Pearl level results in over 37% reduction in cooling load [7]. This result is in agreement with Friess et al. [12] similar study for a Dubai villa, which results in a decrease in cooling load of 29.4% when full perimeter insulation is applied**.**

The buildings that mark the UAE's skylines have mostly been constructed prior to any of these regulations, and thus do not conform (or only marginally) to any regulations, and offer ample room for analysis and implementation of efficiency measures.

3. Building orientation and layout

Building orientation and layout has been shown to be of high importance in reducing building energy consumption in cold and hot climates. A number of factors beyond the building's constitutive elements affect a building's thermal performance, including climatological considerations, building shape and surrounding urban morphology. These factors dictate the amount of precipitation, thermal energy (direct and indirect) and wind (intensity and prevailing direction) that a building is exposed to. As such, early stage planning can be carried out to shape the urban development to best suit these influences, however this awareness is only slowly permeating the UAE building and planning community. In fact, deliberate energetic urban planning represents the best starting point for an energetically optimized urban environment and building composition, as shown by Taleb et al. [18]. They introduce the concept of urban parametric design and apply a genetic algorithm to optimize the layout of a Dubai mixed-use area to develop sustainable and healthy communities. Their initial results indicate possible energetic and ventilation improvements ranging from 8% to 30% over the as-built case; however such innovative strategies have not been considered in the layout of most UAE developments.

Aboulnaga et al. [19] also discuss the effect of urban patterns on building energy consumption by comparing four similar but differently oriented two-story residential buildings in Al Ain. Based on their results, the authors recommend inclusion of energetic considerations in the development of urban patterns. This recommendation is justified by reported energy savings of up to 55% accomplished by limiting fenestration to only two elevations, and restricting the window to surface area ratio to about 1:6. The MASDAR development in Abu Dhabi represents a singular exponent of the application of best energetic practices at all levels, as the entire development is conceived with sustainability and energetic considerations as focal areas, however little quantitative experimental confirmation of the projected energetic savings [20, 21] has been reported in the literature.

The next level of geometric optimization occurs at the individual building scale, and consists of configuring the building's shape and volume distribution in an optimal manner. These considerations, often constrained by the specific characteristics of the planned building and the size, shape and orientation of the building plot, can be quite restrictive in the case of high-rise office and commercial buildings. In these buildings, space needs to be maximized for a given footprint, thus often resulting in “standard” rectangular-shaped office towers [22] that leave only limited room for layout optimization (however, some departures to this model exist, and successfully leverage shape effects to improve natural ventilation [23]). In accordance, low-rise residential buildings and villas offer the highest shape flexibility and thus best potential for energetic shape optimization, and constitute the subject of study for the bulk of the work reviewed in this context.

The directionality of solar radiation due to the sun’s path implies that there are favored directions in which the sun will penetrate deeper into a building through the glazing, thereby increasing the solar heat gain. In the low latitudes of the UAE, sunlight will penetrate deepest into buildings on their western and eastern facades (low sun position at sunrise and sunset) in the summer, and in the western and eastern as well as the southern elevations in winter. Thus restricting fenestration on the exposed sides and/or applying solar control measures to the glazing will improve thermal performance of the envelope. The new green building legislations that are currently being implemented incorporate this insight by prescribing maximum window areas for the different orientations and appropriate solar-control glazing [15]. While specific improvements in glazing and shading are presented in a later section, the building layout can also foster solar control and improved ventilation. The architectural feature of a central courtyard is deeply rooted in the traditional Middle Eastern architecture, and positive results have been reported by a number of UAE based studies.

The courtyard introduces two mechanisms to aid in the cooling of the home. First, fenestration can be concentrated towards the courtyard [24]. This strategy increases shading, and provides less directional solar heat gain sensitivity. Second, the courtyard can be utilized in a number of convective cooling strategies, such as utilizing fountains for evaporative cooling, increasing natural ventilation by improved cross flow and stack effect, and even coupling the ventilation strategy with a wind catcher or wind tower.

Al-Sallal [25], in his comprehensive design study of a sustainable house in the Abu Dhabi desert that includes many of the passive cooling strategies of the courtyard, compared the energetic performance of a house that incorporates a courtyard with one that reflects the typical square form. Keeping all other variables (floor area, shading, glazing, wall insulation levels, etc.) the same, the performance of the courtyard house reduced the cooling energy by 4%, the fan energy by 2%, and the lighting and equipment energy by 21%, resulting in a total electric energy savings of 8%.

Al Masri et al. [24] investigated the inclusion of a central courtyard in a medium-rise residential building in Al Ain. The base building (no courtyard) and the courtyard building retain the same floor area and volume, but the courtyard building has a 47.2% higher external wall area. While the opening area remains unchanged, it follows a different distribution as openings in the courtyard model are primarily directed to the courtyard. Such an arrangement results in a 54.7% reduction in solar gain, as most openings are shaded and located in the controlled courtyard. However, the larger wall area implies an increase in conduction gains through the walls of 54.15%. Upon combining these results, a net reduction of 6.9% in total energy consumption is achieved due to the purely geometrical introduction of the courtyard (all other variables beyond heat gains through the walls and windows are kept constant).

From these results it becomes apparent that courtyards represent an effective architectural component that not only addresses energy savings, but also one that is aligned with the cultural and historic development of the UAE.

4. Wall and roof treatment

Wall insulation levels become an important parameter in energy conservation in residential villas, as window-to-wall ratios are lower than in office high-rises, and more heat is transmitted through the opaque portions of the building envelope. As such, most studies address low-rise villas and apartment buildings. The heat loss in buildings of this type can represent up to 30% of the total building's cooling load [25,26], and thus improving the insulation becomes a critical driver to attain higher energetic efficiency.

In recognition of this importance, all energy regulations introduced in the UAE since 2003 prescribe maximum U-values. However, currently the only regulated Emirates are Dubai and Abu Dhabi, where since 2014 the Dubai Green Building Regulations limit U-values for the roof and walls to a maximum of 0.3 W/m^2K and 0.57 W/m^2K respectively, and the Estidama PEARL code applied in Abu Dhabi, which prescribes (at its lowest rating) maxima for roof and wall U-values of 0.14 W/m^2K, and 0.32 W/m^2K respectively [27].

There are two primary mechanisms that contribute to heat transmission through opaque building enclosures: first, the conduction through the walls due to the temperature difference from inside to outside ambient temperature, and second, additional conduction through the walls due to radiative solar heating of the outside surface of the walls. The mitigation approaches for both mechanisms differ, as the first requires increased insulation, and the second implies decreasing the amount of solar energy absorbed by the outer surface of the wall.

Transmission by conduction is addressed by increasing the wall's resistance to conducting heat. In the context of the UAE typical mass-wall or barrier-wall construction that utilizes reinforced concrete structure and concrete block, this reduction of conduction losses primarily takes on the form of thermal bridge mitigation and increased application of insulation materials.

Friess et al. [12] present an experimentally-calibrated computational study on the role of thermal bridges in the energetic efficiency of residential villas in Dubai. Their analysis notes that the villa, constructed under the Dubai Municipality Directive 66 that prescribes a maximum U-value to be used for the concrete block employed (0.57 W/m^2K), does not specify a maximum U-value for the reinforced concrete structure (the study was carried out in 2011, prior to the implementation of the Dubai Green Building Regulations, which include a qualitative provision addressing thermal bridges). Upon modeling the villa, it was noted that only 24% of the perimeter area is composed of the insulated block (U value of 0.523 W/m^2K), while up to 53% of the perimeter consists of the reinforced concrete structure of the home, which remains un-insulated (U-value of 2.398 W/m^2K). A number of insulation variations were computed, observing both the effect of insulating the thermal bridges to the same standard (50 mm of EPS) than the concrete block (resulting energy savings of 23.3% over the as-built case), to a sensitivity analysis of different insulation thicknesses over a hypothetical un-insulated case (resulting in a 26.8% reduction of the energy consumption for a 50 mm insulation, and a further 7.4% reduction when increasing the insulation thickness from 50 mm to 160 mm). The results underline the importance of adding insulation to the entire opaque envelope, however also show that diminishing returns are obtained upon increasing the insulation thickness beyond a minimum threshold.

In a follow-on study, Rakhshan et al. [28] examined the environmental impact of the increased insulation levels for the same villa, and report that the sustainability cost of adding the insulation is small in comparison to the operational energy savings and GHG emissions.

Radhi [26] conducted a study to assess the impact of using AAC blocks on the energy performance of UAE residential buildings. In this study, the author compares 5 different insulation systems in order to ascertain the effectiveness of AAC blocks as a building/wall insulation material for residential applications. Energetically, 200 mm AAC block is superior to similar wall structures composed of sand-cement block and red clay brick, and only slightly worse (0.05%) than 200 mm sand cement block with 25 mm- 50 mm EPS insulation, however financially it only becomes viable in Sharjah, where the electricity costs are 10 times those of Abu Dhabi (0.013$/kWh in Abu Dhabi vs. 0.13$/kWh in Sharjah, as reported by Radhi [26]). In Abu Dhabi the subsidized electric costs imply that the better-insulated solution is more expensive over the lifetime of the building. The author also calculates the CO_2 savings due to the application of AAC. According to this study, it was found that using AAC can reduce energy consumption in residential buildings by 7%. Also, a saving of 350 kg of CO_2 per square meter of AAC wall is achievable.

Radhi [13] presents a study that projects the implications of global warming on the energy consumption and CO_2 production of the UAE residential sector, analyzing the effectiveness of a collection of measures (including thermal insulation, thermal mass, shading, window to wall ratio, and optimized glazing system) toward mitigating the projected consumption and emission rise. The subject of study was a residential building located in Al Ain, where the author decreased the U-Value of the walls from 2.32 W/m^{2}K to 0.3 W/m^{2}K by adding 35 mm of polystyrene, and similarly for the roof from 0.6 W/m^{2}K to 0.2 W/m^{2}K. This yielded in a 19.3% reduction of cooling energy. Then the author introduced thermal mass (by using 250 mm heavy weight concrete block in place of the original 150 mm lightweight concrete block), in turn decreasing the cooling energy by 13.4%. Results indicate that, among all measures explored in this work (insulation, thermal mass, shading, glazing, and window area), thermal insulation and thermal mass are most effective at decreasing cooling load and overall energy consumption of residential buildings.

Increasing thermal mass in building walls has the effect of time-shifting heat loads; the envelope temperature lags behind the ambient temperature. While no direct studies are reported from within the UAE, studies in similar environments (Saudi Arabia) confirm that increased thermal mass decreases energy consumption: Al Sanea et al. [29] have shown that increased thermal mass is beneficial by decreasing peak transmission loads, and by reducing heating transmission loads through the walls in particular during the moderate months. An important criterion is that insulation should be placed on the outside, so as to minimize the heating of the thermal mass.

Afshari et al. [5] examine the effect of increasing opaque partition insulation in their study of a fifteen-story mixed-use building in Abu Dhabi, reporting a 2.6% annual cooling load reduction upon increasing insulation from a U-value of 1.71 W/m^{2}K to a U-value of 0.324 W/m^{2}K (through the addition of 80 mm of EPS). This low reduction is due to a relatively small opaque partition external area (the building's window-to-wall ratio is 70).

Al Masri [24] presents a comprehensive computational parametric study on the integration of a courtyard into a typical Dubai mid-rise residential building, by quantifying energy savings due to the courtyard form, as well as the effect of increasing the wall thickness, various insulation materials, and increasing wall insulation thickness. The authors explore different thermal masses and different thermal conductivities of the perimeter walls. Results indicate that the building is insensitive to thermal mass, as a decrease from the base case (thickness 25 cm) to 15 cm only generates increased energy consumption of 0.6%, while an increase to 40 cm results in a reduction of 0.9%. In all cases the insulation thickness remained constant at 5 cm. The authors also carry out a comparative between five different insulation materials, and conclude that their respective effectiveness is a function of their thermal conductivity. Upon varying the insulation thickness about the base case (5 cm thick insulation) to 10 cm and subsequently to 2.5 cm, the authors report a 3.6% decrease in energy consumption to an increase of 5.44% of energy consumption respectively. These results indicate similar orders of magnitude to the results of Friess et al. [12], where a decrease of energy consumption of 6.5% is reported upon increasing the insulation from 5 cm to 16 cm.

Table 1 Comparative results of building insulation studies reviewed

Author	Type	Location	Change (U value in W/m2K)	Result (EUI in kWh/m2a)
Friess et al. [12]	Villa	Dubai	Insulating the thermal bridges (54% of enclosure): Adding 50 mm EPS (U from 2.398 to 0.600) Insulating full perimeter: No insulation to 50 mm EPS (U from 2.398 to 0.600) 50 mm insulation to 160 mm EPS (U from 0.600 to 0.226)	23.3% electrical consumption reduction EUI from 220 to 161 (26.8% reduction) EUI from 161 to 149 (7.4% reduction)
Radhi [26]	Villa	Al Ain	Change in U value: Walls U from 2.32 to 0.3 Roof U from 0.6 to 0.2 Change in Thermal Mass: Concrete thickness from 150 mm to 250 mm	19.3% cooling energy reduction 13.4% cooling energy reduction
Radhi [13]	Villa	Al Ain	Change Sandstone (U = 1.64) to AAC (U = 0.16)	7% total energy consumption reduction
Afshari et al. [5]	15 story office	Abu Dhabi	U from 1.71 to 0.324 Observation: building has high window to wall ratio of 0.7	2.6 % cooling energy reduction
Al Masri et al. [24]	Villa	Abu Dhabi	Cellular Polyurethane insulation thickness from: 50 mm (base case) to 25 mm 50 mm to 100 mm Thermal mass from: 250 mm to 150 mm 250 mm to 400 mm	5.44% energy consumption increase 3.6 % energy consumption decrease 0.6% energy consumption increase 0.9% energy consumption reduction

Table 1 shows a summary of the results discussed above. It demonstrates that the addition of insulation is critical to decrease the energy consumption of buildings in the UAE, as all reviewed studies indicate improvements upon adding insulation or increasing the thickness of the insulation. Results indicate that any thickness is effective, with diminishing results as the thicknesses increase. In particular thermal bridges, if left untreated, can represent a large un-insulated fraction of the building, effectively negating any insulating effect prescribed by the building code. Thermal mass follows the same trend, however both studies that address its effectiveness report improvements that differ by an order of magnitude. Additional work indicates that in order for the thermal mass to provide optimal results, the insulation should be placed on the outside of the wall.

5. Wall and roof solar absorption

Solar absorption on external surfaces has a significant impact on heating of the wall beyond the ambient temperature, and thus will increase conduction through the wall and directly impact the cooling loads.

In recognition of this effect and since 2014, the Dubai Green Building Regulations mandate for all new buildings in the Emirate, that at least 75% of the area of externally painted walls have a minimum light reflective value of 45%, and a minimum Solar Reflective Index of greater than 78 for flat and low sloped roofs. Further, the use of green roofs is rewarded [15].

Radhi [30] evaluated the impact of different wall cladding systems on direct and indirect CO_2 emission of a three-story academic building in Al Ain. The base-case building has an overall area of 4500 m^2 with set-points of 22°C to 24°C in summer and 20°C to 22°C in winter. The window-to-wall ratio varies between 0.24 and 0.37 depending on the façade orientation. Operational energy and CO_2 is modeled using the Design Builder front-end to EnergyPlus. Studied systems in this paper include stucco, masonry veneer, aluminum siding, vinyl siding, and exterior insulation and finish systems (EFIS). While primarily focusing on the optimization of the cladding systems with regards to CO_2 emissions, the study specifically reports on the sensitivity of the cooling loads to the absorption coefficient of the outside surface. Results indicate that the heating and cooling energy utilized by the building is inversely proportional to the absorption coefficient of the outside cladding material. While these results could be caused by the differing U-value for each cladding system (where again a mass-wall utilizing EFIS displays the lowest U of 0.523 W/m^{2}K, and masonry the highest U of 1.513 W/m^{2}K), the authors present sensitivity results that isolate the impact of the absorption coefficient onto the heating and cooling loads: the cooling load required using EFIS (with a low absorption coefficient of 0.17) as a cladding system is about 126.5 kWh/m^2, this increases to 129.0 kWh/m^2 in the case of masonry veneer (with the worst absorption coefficient of 0.55). This corresponds to a difference of 1.9% in the heating and cooling load.

Taleb [31] includes a reflective white poly insulation with an R-value of 15.76 m^{2}K/W in a study of a typical Dubai villa, and includes a reflective coating with a 61% reflection, however does not report the savings caused by this specific retrofit, rather only reports the overall effect of all measures (including evaporative cooling, window retrofit, natural ventilation and external louvers) to be 23.6% savings over the as-built case.

K.A. Al-Sallal et al. [25] designed a sustainable house in the desert of Abu Dhabi using Estidama Guidelines and rating methods along with referring to other standards or less formal documents such as LEED Homes or Resolution 66 of Dubai Municipality (DM). The authors implement the U-value requirements for the envelope as per DM Resolution 66 (0.57 W/m^{2}K for walls, and 0.44 W/m^{2}K for floor slabs and roof), which resulted in an energy reduction of up to 40% over a reference case that incorporates the material assemblies typically found in an Emirati house (albeit without specifying these or the associated transmittance). However, the authors present quantitative energy savings attributed to shading of the perimeter, thereby avoiding direct and reflected solar heating of the walls. These landscaping measures reduced the thermal load through the walls by 18.4% (and 31.4% through the windows), materializing in an overall reduction of cooling energy of 6% and fan energy by 8%.

M. Haggag et al. [32] introduced a green wall to decrease heat gain through the envelope of a school building in Al Ain. Photovoltaic panels were employed to generate the electricity for the lighting and irrigation system of the green wall. In this experimental study the green façade was examined in situ to assess its performance in hot and arid climate of Al Ain. Two identical east facing classrooms, one with the green wall and the other one bare, were selected. The measurements show that the green façade can regulate the shaded wall external temperature by 5˚C to 13˚C during the day. While during the night the green wall acts like a thermal insulation through trapping heat inside, the results show that the internal wall temperature of the green façade is always lower than that of the bare wall which results in continuous energy saving throughout the day.

Taleb [31] includes a green roof as a passive cooling strategy in the performance model of a Dubai villa, however does not provide details on the type of green roof utilized or the specific performance improvement due to the green roof.

Table 2 Comparative results of studies addressing solar absorption of opaque building enclosures.

Author	Type	Location	Change	Result
Radhi [30]	3 story academic building	Al-Ain	Changing wall cladding systems: Stucco, Masonry veneer, Aluminum siding, Vinyl siding, Exterior Insulation and Finish systems (EFIS)	EUI is proportional to absorption coefficient: EFIS (abs. coef. 0.17) results in EUI of 126.5 kWh/m^2, vs. masonry veneer (abs. coef. 0.55) EUI of 129.0 kWh/m^2 (1.9% reduced heating and cooling load)
Taleb [31]	Villa	Dubai	Use of reflective white poly insulation with an R value of 15.76 m^2 K/W with 61% reflection	Energy saving not specified
Al-Sallal et al. [25]	Villa	Abu Dhabi	Use of landscaping measures such as Palm trees, ornamental trees and aqueous plants as well as grass ground cover to avoid direct and reflected solar heating of the walls	18.4% reduction in thermal loads through walls and 31.4% through windows 6% saving in cooling energy and 8% saving in fan energy
M. Haggag et al. [32]	School	Al Ain	Introduction of green wall	Reduction of external wall temperature by 5˚C to 13˚C during the day

The above results indicate that reducing solar heating of the outer surface of the wall contributes to cooling energy savings. The two strategies reported include using exterior wall surfaces that boast a lower solar absorption coefficient (with reported cooling load savings of up to 1.9%), as well as the use of vegetation both as shade generators detached from the building, and for greening the roof and walls. The latter has been shown to be effective in a number of scenarios and additionally reduces the solar heat gain through the windows [33], while the former introduces the advantage of additional evaporative cooling on the structure, albeit at a higher level of constructive complexity, and potentially higher water use.

6. Windows

Building glazing fulfills a twofold mission: it allows light in for occupant comfort, but also provides a physical barrier to the outdoor conditions. Daylight in the workplace is an important contributor to occupant wellbeing and reduces lighting electricity demand; as such, increasing window area is a common practice. However, and of particular importance in the UAE due to the local very high solar irradiance [6], excessive direct sunlight causes glare, which in turn negatively affects occupant wellbeing. To counteract glare, measures have to be taken to transform direct sunlight into indirect and ideally diffuse light, and this is often accomplished by either exterior or interior shading. The second mission of window glazing is one of physical barrier, which in the thermal context implies reducing heat transmission from the hotter outside environment to the cooled inside environment. This heat transmission takes on three primary forms for closed windows: first, conduction through the glass, second is solar heat gain by radiative transmission through the glass, and a third mechanism is conduction through the window frame. The latter, and due to the low area and often included thermal break in window frames, is often not as significant.

The practical considerations described above are not the only drivers that come into consideration in office buildings, but aesthetic and architectural standards often dictate the appearance of the buildings. In particular, full glass enclosures have become the norm worldwide for office towers [34]. The reason for this preference is that daylighting represents an optimal strategy to enhance occupant wellbeing and decreases lighting cost, which can be (in more moderate climates) the single largest energy consumer of the building. However, in the climatic and solar context of the UAE, daylighting can produce adverse effects of excessive light and glare.

Aboulnaga [34] reports that Dubai receives solar irradiance of up to 850 W/m^2 during the summer, with associated sky illuminance levels ranging from 75,000 lx to 107,500 lx. These levels far exceed the optimal indoor daylighting levels that range from 300 lx – 2000 lx and thus, unless great care is taken in glazing selection and shading, the light levels become excessive and can result in a negative effect on occupant comfort and solar heat gain. Al-Sallal [35] reports similar findings of 3-4 times the daylighting levels of 2000 lx recommended for architectural studios and task lighting, and Mokri et al. [6] confirm these findings of very high irradiance.

In recognition of this effect, the Dubai Green Building Regulations implemented in 2014 now require at least 50% of the glazed areas to be on the north side of the building, and require environmental treatment of the South and West glazed areas. In addition, minimum glazing requirements (for over 60% glazed buildings) demand a maximum U value of 1.9 W/m^{2}K, a maximum shading coefficient of 0.25, and a minimum light transmittance of 0.1 [15].

Thus the trend of fully glazing office towers seems to not be directly transportable to the UAE without implementing shading measures that reduce glare and excessive lighting levels in the daylit zones (about 2.5 times the height of the opening away from the window in side-lit scenarios, as are common in office towers), as well as limiting solar heat gain to reduce cooling requirements; Al-Sallal [36] states that "designing buildings based on ready-made foreign standards and past experiences that do not necessarily fit into the desert environment". Reducing the amount of light transmission in fully glazed façades is typically accomplished using external and internal shading, window films, and high performance glazing.

Aboulnaga [34] surveys the glazing solutions of 15 office buildings in Dubai as to their light transmittance, reflection, shading coefficient (SC), and relative heat gain, by splitting them into three categories (high, intermediate and low performance). High performance buildings were defined as those with glazing having a shading coefficient of 0.12-0.29 (significantly below the 0.35 limit established by the Dubai Municipality); intermediate performance buildings were those with a SC between 0.31-0.35, and low performance buildings with SC ranging from 0.36-0.46. The medium-to-low performance buildings have required a number of retrofits (such as external louvers) and occupant solutions such as venetian blinds and even aluminum foil to control the excessive heat and glare. A subsequent computational case study of daylighting levels using a building from the intermediate group reveals that the use of clear glass in unobstructed buildings can generate daylighting levels of more than 10,000 lx. As a result of his work, Aboulnaga recommends a shading coefficient of less than 0.2, and discourages large glazed areas.

Al-Sallal contributes work on daylighting issues in classrooms and in the Architectural Engineering Building at UAE University [33,36]. The author discusses the effectiveness of shade trees to improve lighting distribution and quality in classrooms, as many are inappropriately lit allowing excessive direct sunlight to enter the space. The resulting high brightness contrast and acute glare generates occupant discomfort to the extent that windows are covered with paper or drapes, thus negating the intended positive daylighting effects. Al-Sallal [33] also reports on the effectiveness of shading trees in blocking direct sunlight but generating reflected sunlight (diffuse light without glare), with results supporting the use of Ghaf or Neem trees (evergreen) to improve the quality of natural lighting, as only a minor increase in electrical lighting is needed to illuminate the back spaces.

Hammad et al. [37] address the solar heat gain through glazing by incorporating dynamic external louvers as shading devices in an office building. Their computational study analyzes the effect of static and dynamic external louvers when added to a fully glazed office suite with glazing corresponding to the low performance building category of AboulNaga's study (SC of 0.41 and 0.76 with a U value of 1.95 W/m^{2}K). The maximum reduction of total energy consumption ranges between 28% and 34% when utilized in conjunction with interior light dimming control (keeping the interior ambient illuminance levels at 500 lux). The use of static louvers was marginally less effective than the dynamic case. The louvers were least effective on the east and west facades, where light dimming technology is sufficient. In contrast to Hammad's work, Al-Sallal [36] argues that due to increased maintenance requirements in the high dust UAE environment, exterior dynamic shading systems are not recommended, favoring systems located in the glass cavity or within a double façade.

Radhi et al. [38] analyzed the impact of multiple façades systems on the overall energy consumption of fully glazed buildings. They modeled the Architectural Engineering Building in UAE University using Building Energy Simulation software coupled with RANS CFD to analyze the airflow between the façades. The results quantify the energy usage differences between a single façade and a double façade system to be between 17% and 20% on a sunny day.

Afshari et al. [5] analyze a series of retrofit measures toward their energetic and sustainability impact by modeling a 15 story mixed-use office type building with 70% window to wall ratio with continuous horizontal glazing with a U value of 2.4 W/m^{2}K and a solar heat gain coefficient of 0.36. Two types of glazing retrofits are applied (double pane, low-gain, low-e insulated frame and either Argon filled or Air filled, resulting in U values of 1.47 W/m^{2}K and 1.7 W/m^{2}K respectively and a SHGC of 0.3 for both), with results indicating a peak load reduction of up to 4.2%, and an annual cooling load reduction of up to 4.6%.

Friess et al. [12] discuss the role of improved fenestration in the overall energetic consumption of a UAE villa in the context of envelope insulation specific work. They quantify the window area of the UAE single family home used in their study to be 21%, with sliding windows having thermal control double pane glass (24mm) with a U value of 1.8 W/m^{2}K, a SHGC of 0.37 with visible transmission of 41%. Only limited exterior shading is used. Given the low window-to-wall ratio and the residential use, daylighting is not a primary driver and improving the fenestration has little effect on the overall energy consumption; the authors quantify that replacing the glazing with highly reflective, low-emissivity triple glazing generates an improvement of 4.6% over the base case.

AboulNaga [19] presents a case study located in the city of Al Ain, where he analyzes four two-story residential buildings integrated into the urban grid, but oriented differently. Results indicate for the case studies reported (building sites oriented at 30° North East), that limiting windows to only two orientations at 60° North-East has the potential to reduce energy consumption by up to 55% over the existing more regular window distribution and single pane glazing.

Taleb et al. [31] incorporate a change in glazing (from single glazing to Argon filled double glazing with solar control film, resulting in a SHGC of 0.17) to their overall analysis of the effect of 8 passive cooling measures on a villa in Dubai, and report that the combined effect of all measures reduces demand by 23.6%. However, the specific effect of the glazing change alone is not reported.

Al Masri et al. [24], and in the context of the study of courtyard integration into mid-rise residential buildings, also examines the energetic effect of improving glazing. The glass type is varied from single glazing, to double glazing low-e, to triple glazing low-e, and thus focuses primarily on heat conduction through the windows, and not solar heat gain. The reference model incorporates double low-e glazing, and results indicate that single glazing increases energy consumption by 12.31%, while choosing low-e triple glazing only improves energy consumption by 2.32% over the base case. These results are obtained in the framework of a low opening to wall ratio of 14%, and without attempting to decrease the SHGC of the glazing using reflective coatings.

In a design study for sustainable house in the Abu Dhabi desert [25], Al-Sallal utilizes vegetation to reduce direct and reflected solar heat gain, attaining a 6.6% reduction in the annual cooling load. Further work by the same author includes model testing of the UAE University Architectural Engineering Building [35] addresses adding a reflective light shelf to increase backspace illumination level, which only demonstrates seasonal effectiveness, as well as confirming the positive effect of adding translucent layers to the skylights.

Table 3 Comparative results of glazing and shading studies reviewed.

Author	Location	Type	Actions	Results
Radhi et al. [38]	Al Ain	University building (100% glazing)	CFD and building energy simulation of impact of climate interactive façade systems	17% to 20% reduction in cooling energy
Afshari et al. [5]	Abu Dhabi	15 story mixed-use (70% glazed)	Improve glazing from U 2.4 and SHGC 0.36 to: U 1.7, SHGC 0.3 U 1.47, SHGC 0.3	3.5% annual cooling load reduction (3.6% peak) 4.6% annual cooling load reduction (4.2% peak)
Hammad et al.[37]	Abu Dhabi	Office (60% glazed)	Addition of external dynamic louvers in combination with interior lighting control	28% to 34% reduction of total annual energy consumption
Friess et al. [12]	Dubai	Villa (21% glazed)	Change double glazing (SHGC 0.37) to high reflectivity, low-e triple glazing	Up to 4.6% reduction in annual energy consumption
Aboulnaga et al. [19]	Al Ain	Two story residential	Analyzes optimal positioning and window area	Up to 55% reduction in annual energy use by limiting windows to two elevations (60 North-East) and 10%-20% window to wall ratio
Taleb [31]	Dubai	Villa	As part of eight passive cooling strategies louvers and glazing change from single to double low-e Air filled were modeled	Reduction of 23.6% of all measures combined (no individual result due to glazing and window treatment given)
Al Masri et al.[24]	Dubai	Mid-rise residential (14% glazed)	As part of a study regarding integration of a courtyard, changes in glazing were analyzed: Changing from single pane to double pane low-e Changing from double pane low-e to triple pane low-e	12.31% reduction of total energy consumption

				2.32% reduction of total energy consumption
Al-Sallal et al. [25]	Abu Dhabi	Villa	A range of vegetation and landscaping based shading measures were taken in a study of a sustainable house	6.6% reduction in total energy consumption due to shading

The above results indicate that appropriate fenestration levels and glazing choices constitute a critical factor for energy efficiency in buildings in the UAE, in particular in mixed-use and office buildings, with lower sensitivity in villas as they boast significantly lower window-to-wall ratios and less dependence on daylighting for their use. The absence of regulation and improperly implemented building trends from other parts of the world have resulted in buildings with excessive glazing and poor choice of glass, in turn resulting in very high solar heat gain through the windows, improper daylighting levels and high glare conditions, as well as significantly increased cooling energy demand.

7. Natural ventilation

Natural ventilation has the potential to reduce energy consumption by convectively cooling the building's interior, while at the same time contributing to good indoor air quality. The concept relies on an air exchange with the outside that is typically driven by pressure and temperature differences, and that does not rely on mechanical systems.

Perhaps the most characteristic exponent of natural ventilation in traditional Arab architecture is the wind tower, or wind catcher (Fig. 2). The wind tower takes advantage of the pressure differences generated by wind around a building, and generates a cross-flow in the building by positioning the inlet in a high pressure area, and the outlet in a low pressure area [39]. If there is no wind, the wind catcher utilizes the stack effect (buoyancy due to temperature differences at different elevations), and the inlet acts as outlet for the stack, however research has shown that wind-driven ventilation in a wind catcher will provide 76% more ventilation than buoyancy driven ventilation [39]. To enhance the ventilation rate, a wind catcher may be combined with a separate solar chimney.

Fig. 2. Badgir Wind tower in Dubai.

Hughes et al. [39] provides a comprehensive review of the development and building integration of wind towers. Important design considerations are height (as wind speed will increase with elevation), position (to minimize the effect of surrounding structures), and alignment with the prevailing wind direction. In order to be located in the highest-pressure area, the wind catcher opening should be at the windward side of the roof for a location with a clearly prevailing wind direction, or at the center if multi-directional wind is the norm. The height is chosen to ensure that rooftop turbulence does not affect the air inlet. In addition, in the hot and dry areas of the Gulf, added height will also decrease the dust and pollution intake.

Wind catchers may be unidirectional or multidirectional, with partitions to create multiple shafts, where only the windward one will be active as inlet, and the other shafts will be functioning as outlet. Rectangular cross sections show higher performance than circular cross sections. While multiple shafts decrease the overall airflow, such a wind catcher will be less sensitive to changing wind conditions. In particular the four sided Badgir (Fig. 2), which was developed in Iran in the 9th century AD [40], has found widespread application in the UAE [41,42].

While the traditional wind catcher does not incorporate any active cooling, their effectiveness is limited in areas with high outdoor temperatures. In these hot arid regions cooling devices can be integrated into the wind catcher design, an example being the incorporation of evaporative cooling pads, columns, or underground water streams over which the air passes before entering the building [39].

Wind towers are also often applied in conjunction with a courtyard to further enhance cross ventilation [25], which represents another typical element of Middle Eastern traditional architecture.

There is ample literature on the effectiveness of wind towers, as well as a number of specific examples of their application in Iran, however in the UAE, and in the context of modern construction developments, the wind tower has largely remained an aesthetic element mimicking vernacular architecture [42], but without its intended functionality (Fig. 3). Only in very recent years and due to the increased awareness of energy efficiency, has the wind tower received renewed attention as a functional building element in the UAE.

Fig. 3. Villa development in Abu Dhabi incorporating fake wind towers.

A UAE based computational example is provided by Taleb [31]. The author analyzes a number of passive cooling strategies in the context of a newly constructed villa in Dubai, modeling the natural ventilation effect of a wind catcher and cross-ventilation. The wind catcher is computationally modeled at a height of 10 meters in order to remain outside of the rooftop turbulence field, and its louvered opening points into the prevailing wind direction in order to route airflow into the building. In the context of this study, enhanced crossflow was achieved by opening the terraces and windows in the computational model. The results presented do not single out the performance of the natural ventilation strategies, but combine the savings for all eight energy efficiency modifications considered (light color with high reflection, indirect radiant cooling, evaporative cooling using a fountain, improved insulation, green roofing, the natural ventilation techniques described, as well as exterior louver shading and double glazing). The overall energy savings reported were 23.6% over the original building.

Al-Sallal [25] introduces the wind tower and courtyard elements of Emirati vernacular architecture in the design of a sustainable house in the Abu Dhabi desert. The authors incorporate two wind towers into the design, functioning as wind catchers during cool nights and as solar chimneys during daytime to evacuate excess heat from the home. The results presented include a number of other passive measures, without attributing specific results to each measure; however the collective effect indicates savings potential of 59% in greenhouse gas emissions and utility bill over the base case (a similar home built according to Dubai Municipality Decree 66 regulations).

The above studies show that there is increased interest in the wind tower as a functional energy efficiency element, however their implementation in the UAE to date remains at exploratory levels in isolated design studies. Possible barriers for implementation can be found in the perceived higher indoor air temperature variations and quality (dust-loading) that wind towers provide over normal air conditioning, the more rigid architectural layout constraints that effective wind towers require, and higher construction costs coupled with low and subsidized electricity costs. However, emerging energy efficiency regulation coupled with increased appreciation of the integration of traditional building elements that reinforce historic identity in architectural solutions may support a more widespread implementation of wind towers.

Additional natural ventilation strategies include generating cross-flow through the windows, mixed mode ventilation, as well as using solar chimneys and the stack effect to enhance airflow into the building.

Taleb [43] examines the natural ventilation levels attained in a Dubai villa in 5 scenarios, with different durations of ventilating the building by opening the windows during the winter months, and provides computational results regarding the energy consumption and temperature fluctuations for each case over the base case (where the AC operates year round, with no natural ventilation). Results indicate that all scenarios including natural ventilation offer energy savings over the base case, however with different degrees of temperature deviations from the envisioned set point of 22 °C. In particular, operating the AC only during the summer months and utilizing natural ventilation in winter offers up to 30% energy savings over that base case. An additional result was that the savings in the different scenarios remain insensitive to a building rotation by 45 degrees from its original orientation.

Due to the high solar irradiance, solar chimneys represent a viable ventilation technique in the UAE. Solar chimneys function on the basis of the stack effect, generating temperature driven buoyancy convective flows. In order to maximize the natural convection, the solar chimney needs to heat the air as much as possible, and thus typically solar collectors are included to heat the air.

Aboulnaga [44] presents a theoretical analysis of the optimum geometry of an inclined roof solar chimney with absorber plate coupled with an evaporative cooling cavity at the inlet in a two story residential building in Al Ain. Results indicate maximum volume flow rates of 0.81 m^3/s at an average solar radiation of 850 W/m^2. A follow-on study by the same author [45] further extends the theoretical optimization of the chimney configuration by adding a wall portion (wall-roof solar chimney) yielding airflow rates of 2.3 m^3/s, resulting in up to 26 air changes per hour for a single family house in Al Ain. The authors suggest that night time ventilation at this rate is sufficient to provide the required cooling for a heavy residential building [45].

The above studies show that natural ventilation has been studied and implemented in the UAE primarily in low-rise residential units. High-rise and mixed-use buildings generally rely on air conditioning year round to maintain appropriate indoor conditions, and do not include owner-operated or wind or stack effect driven ventilation (studies report that using passive natural ventilation in office buildings has been found to be insufficient in order to maintain thermal comfort [46]). However, combining active systems with passive ventilation strategies can take advantage of mixed-mode ventilation, which implies supplementing the active systems with outside air when the exterior conditions are suitable (often winter time or nighttime conditions).

While no reports regarding buildings in the UAE were available, Ezzeldin et al. [46] explores variations in mixed-mode ventilation and low energy cooling systems in office buildings in a number of arid climates, one of which (Manama, Bahrain) closely resembles the UAE conditions of average temperature and humidity. An intermediate single story of a building optimized for best annual plant demand and employing three different active system configurations (VAV, CAV, and CAV combined with radiant cooling) was used as the base case in the study, and five variations of cooling strategies including natural ventilation were assessed: simple mixed-mode during work hours, mixed-mode during work hours with a nighttime convective cooling strategy, mixed-mode combined with evaporative cooling, mixed-mode with radiant cooling coupled with a cooling tower, and mixed-mode with radiant cooling coupled to borehole heat exchangers. While a heat balance based computational model was used for the fully active system base cases, an adaptive computational model was employed for the mixed-mode cases, including the expectation of adaptive occupant behavior and acceptance of a wider range of room comfort conditions, which implied that the set points for the mixed-mode systems could be higher that the set points for the active systems. Results indicate that:

- Due to high ground temperatures, borehole heat exchangers coupled with radiant cooling are not feasible in climates similar to the UAE
- Evaporative cooling systems show significant energy savings, and including the energetic cost of desalinating the water required only increasing the total system energy consumption by 5%
- Using simple mixed-mode systems over base case VAV systems results in plant energy savings of between 35% and 63%
- Using night ventilation in addition to mixed mode ventilation further increased energy savings to 56% to 79% over the VAV base case
- Using mixed-mode ventilation in conjunction with a cooling tower for the slab radiant cooling (no night ventilation) resulted in energy savings from 55% to 73% over the VAV base case, and savings of up to 25% over the simple daytime mixed-mode system

The results show a very high potential for variations of mixed-mode ventilation in arid climates. However, and due to the significantly wider range of internal set points adopted in the adaptive mixed-mode model than in the VAV base case (computed using an energy balance), savings simply due to occupant behavior (and related tolerance of a wider range of interior comfort conditions) may play an important role in the values reported by Ezzeldin [46].

Table 4 Comparative results of natural ventilation studies reviewed

Author	Location	Type	Actions	Salient Results
Taleb [31]	Dubai	Villa	A wind catcher and cross ventilation is modeled in conjunction to 6 further passive cooling strategies	Reduction of 23.6% of all measures combined (no individual result due to ventilation strategies given)
Al-Sallal et al. [25]	Abu Dhabi	Villa	Two wind towers and a courtyard were included in a design study of a sustainable house as part of a number of additional passive cooling measures	Collective effect of all measures is a 59% reduction in GHG emissions and utility bill; individual performance of ventilation strategies is not presented
Taleb [43]	Dubai	Villa	Impact of 5 cross ventilation timing schedules (daily and seasonal) on energy and interior temperature	30% savings in total energy by using natural ventilation instead of AC during the winter months
Aboulnaga et al. [44,45]	Al Ain	Two story residential	Investigation of the attainable flow rates for a different solar chimney configurations	Flow rates obtained (up to 26 air changes per hour) sufficient to provide required cooling for a residential building

Ezzeldin et al. [46]	Manama (Bahrain)[1]	Office high rise	A number of mixed mode ventilation combinations were explored	Using mixed mode ventilation over base case VAV yields plant energy savings of up to 63% Augmenting mixed mode ventilation with night ventilation yields savings of up to 79% over base case VAV

The above results indicate that natural ventilation is an effective passive cooling strategy that should receive more attention to reduce the environmental footprint of the UAE built environment. The strategies are based in or evolved from pre-air conditioned times, however have been neglected due to the cheap availability of electricity and cooling by mechanical means.

8. Further occupant-based measures

Occupant behavior and interior set points play a critical role in energy conservation [47], and while they do not constitute a part of the building envelope, a number of the studies reported in this review include energy savings results based on a change of internal set point. The magnitude of the reported energy savings based on increasing the set point provides a sharp contrast to the expense and effort required to achieve similar savings using constructive measures [2].

Friess et al. [12] report that changing the interior set point of a typical UAE villa from 22°C in the living areas and 21°C in the bedrooms to 25°C and 24°C respectively generates on the order of 40% energy savings over the poorly insulated as-built case, reducing to 14.3% for a fully insulated perimeter.

Radhi [13], and in the context of UAE residential buildings, reports the possibility of similar savings (between 26.8% and 33.6%).

Afshari et al. [5] examines a number of retrofits (including adjusting the internal set point) of a fifteen story mixed-use office building built prior to any energetic standards being implemented in Abu Dhabi. The cooling set point in the base case is 22°C. The authors report that by increasing the set point to 23°C, 24°C, 25°C and 26°C, the annual cooling load reduces by 8%, 16%, 23% and 29% respectively.

AlFaris et al. [48] examined the effect of a range of envelope and systems retrofit measures on 10 villas in Abu Dhabi, reporting that the combined effect (no detailed listing of individual savings is provided) ranges from 14.4% to 47.6% in electricity savings. The authors report that the difference in the individual energy performance of the villas was a caused by differing levels of occupant understanding and associated energy saving behavior.

The astounding numbers reported in these studies underscore the importance of occupant behavior and popular awareness of environmental considerations in the overall scope of energy savings in the UAE.

9. Conclusion

The studies reviewed here confirm that building envelope measures have the potential to significantly reduce the energetic footprint of the UAE built environment, which over the past four decades has been shaped by the lack of energetic codes combined with the need for rapid construction due to the frantic growth of the country.

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[1] While this building is not located in the UAE, the climatic conditions in Bahrain are very similar, and thus these results offer insights into possible strategies applicable to the UAE.

These measures can be developed at different scales; while large scale urban planning has been shown to be able to improve dwelling cooling and ventilation between 8% and 30%, more modest small-scale envelope optimization, in particular orientation and surface area of windows, can reduce up to 55% of the cooling load in a residential building. Further architectural solutions, such as the culturally and historically rooted addition of a central courtyard, has also shown promising effects on reducing solar heat gain and improving natural ventilation in low rise residential buildings, with reported energy savings between 6.9% and 8% over different base cases.

Heat transmission through opaque building enclosures has been shown to be a significant energy loss mechanism, in particular in residential buildings as they exhibit lower window-to-wall ratios than the glass dominated office high-rises. Adding insulation to otherwise un-insulated walls is highly effective; all reviewed studies indicate improvements upon adding insulation or increasing the thickness of the insulation, albeit with diminishing returns as the insulation thickness increases. Thermal bridges are a common occurrence, in particular in buildings built under early regulations prescribing at least some insulation, and studies show that addressing these can significantly reduce building energy consumption.

In order to reduce the heating of external surfaces (which in turn increases heat conduction through the walls), two primary strategies have been reported: the use of external cladding systems that reduce the solar absorption (reduction of up to 1.9% in the building cooling load), as well as the use of vegetation both as shade generators detached from the building, and for greening the roof and walls.

Windows and glazing constitute a critical link in achieving better energetic efficiency in building enclosures in the very high solar irradiance UAE climate. Addressing solar heating through windows becomes more important in mixed-use and office high-rise buildings, which often follow the global trend of being fully glazed, than in the residential environment, where glazing only occupies a small fraction of the building enclosure. The reviewed work indicates that while changes in glazing from single pane to double pane solar control can have a significant effect (over 12% in the case of a mid-rise residential building), further improvements in glazing again show diminishing returns. However, external shading in the form of louvers and/or vegetation has shown to be highly effective (28% to 34% in cooling energy). In addition, these shading strategies also improve excessive lighting levels and solar glare. Proper window orientation has been shown to decrease energy consumption by up to 55%.

Natural ventilation represents a challenge in the hot climate of the UAE, and has not received much attention since the advent of cheap electricity and air conditioning has allowed direct control of indoor comfort levels. However, the current renewed attention to energy conservation is generating a number of exploratory studies on this subject, with encouraging results. In particular, in low-rise residential buildings the use of natural ventilation strategies during the times when the outdoor climatic conditions allow for natural cooling (simply by opening the windows instead of operating the air conditioning) has been computationally examined, with reported savings up to 30% of the cooling energy. In addition, components of the traditional Middle Eastern architecture such as the wind tower and the courtyard, in combination with solar chimneys, are being reintroduced and analyzed for feasibility under modern indoor comfort level requirements. The studies also extend to quantitative assessment of using mixed mode ventilation in high-rise buildings in similar climates, again reporting energy savings from 35% to 73% depending on the strategy employed.

The above conclusions indicate that very significant energy savings can be attained in the UAE by addressing the building envelope and implementing low energy ventilation strategies. However, in order to effectively enact these savings, it is not sufficient to implement stricter regulations for new construction, but also to develop retrofit measures that can be applied to the extensive existing building stock. In addition to these measures, increasing the public awareness of the effect of occupant behavior on the utility bill, which in the studies reviewed here has been reported to decrease energy consumption between 8% and 40% depending on the specific building characteristics, should provide a strong contribution toward mitigating the excessive energy consumption and environmental footprint of the UAE.

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A review of passive envelope measures for improved building energy efficiency in the UAE

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Abstract

The United Arab Emirates' (UAE) hot climate, coupled with the extreme demographic and urban growth experienced over the past four decades, has shaped a built environment where energetic quality of construction has been superseded by the quantity of construction needed to support the country's growth. This development is further aggravated by the slow development of energetic building codes, as well as the subsidized cost of electricity. The result is that the UAE consistently leads the list of countries with the highest environmental footprint, and the electricity production required to drive building cooling constitutes the brunt of the emissions balance-sheet. The work presented here reviews primarily UAE-based research that addresses the effectiveness of passive building-envelope measures that reduce energy consumption. A number of measures have been developed in response to the increasing demands of emerging energy regulations, and include measures specific to the building envelope in the planning phase or as retrofit, including radiative, convective and conductive heat transfer through walls, windows, roof, as well as energy efficient natural ventilation techniques. This review is geographically restricted to the UAE as its development challenges are directly tied to its distinct economic growth pattern and specific legislation implemented to address energy efficiency. Results confirm the importance of the following factors for energy-optimized structures: building orientation, thermal insulation (which can generate in excess of 20% energy savings in particular in the residential context), appropriate glazing type and orientation in highly glazed office buildings (up to 55% energy savings reported), excessive light levels and glare, and natural ventilation, which can reduce energy consumption from a reported high of 30% in villas to up to 79% in a high rise office building using mixed mode ventilation.

Keywords: UAE; Energy efficiency; Building envelope; Wall insulation; Windows; Natural ventilation

Abbreviations:

HVAC	Heating, Ventilation and Air Conditioning
GDP	Gross Domestic Product
DPW	Department of Public Works
USGBC	US Green Building Council
LEED	Leadership in Energy and Environmental Design
U-value	Heat transmittance through a building component (W/m^2K)
EPS	Expanded Polystyrene
AAC	Autoclaved Aerated Concrete
EUI	Energy Utilization Intensity (kWh/m^2 a)
SHGC	Solar Heat Gain Coefficient
GHG	Greenhouse Gas
CAV	Constant Air Volume

VAV	Variable Air Volume

1. Introduction

The worldwide building sector consumed 32% of the global final energy in 2010, and was responsible for one-third of global CO_2 emissions [1]. Building energy consumption is particularly pronounced in extreme climates, where indoor space conditioning constitutes the largest portion of a building's energy needs. In both cold and hot climates, active systems have to either heat or cool the building to maintain occupant comfort. Further, humidity levels must be kept at acceptable levels, and sufficient fresh air has to be delivered to ensure a healthy environment for occupants. Thus a building's energy consumption is governed by climatological factors, technical factors (energetic quality of the building's envelope and space conditioning), and occupant behavior [2].

In cold climates most energy is consumed by on-site burning of biomass and fossil fuels to generate heat, while in hot climates the space conditioning systems typically rely on electricity as energy source. Energy efficiency strategies however are similar, as heat is lost or gained through the building envelope. Conduction losses through the wall and windows are mitigated in both cases by decreasing the enclosure's U value. Radiative losses or gains however receive a different treatment, as in cold climates they are desirable to reduce heating load, whereas in hot climates they increase the cooling load. Thus in climates like the UAE, window treatments in the form of selective coatings and the appropriate design of shading elements become critical fenestration components. In both cases, and in order to minimize energy consumption, it is important to first optimize the envelope and then address the active heating or cooling systems, as these can consequently be sized for a smaller load.

On the long term, and taking into consideration climate change, worldwide heating energy demand is projected to decrease by 34% by the year 2100, while cooling demand is estimated to increase by 72% over the same time period [3]. Thus the already severe cooling need of buildings in arid regions is projected to increase over the next century, further impacting the often poor energetic and sustainability balance sheet of these regions, and underscoring the necessity of energy efficiency measures.

The UAE's extreme climate generates a challenging environment for energy conservation and environmental sustainability of buildings [4]. The temperature (wet bulb design temperature of 30.6°C and dry bulb design temperature of 45.0°C [5]) and humidity (80% in winter and 70% in summer [5]), combined with the high solar irradiance (yearly average global horizontal irradiance in excess of 20 MJ/m2/day [6]), make air conditioning a necessity to maintain acceptable indoor comfort levels. The resulting electric load attributable to HVAC equipment accounts for 40% of the total year average electrical load, and up to 60% of the summer peak load [7].

The challenges that arise due to these extreme climatic conditions are further compounded by the exponential growth of the country since its formation as a federation of seven Emirates in 1971. The UAE's Gross Domestic Product (GDP) has risen at an average rate of 4.9% annually from 30 Billion $US in 1980 to 81 Billion $US in 2003, and the resulting population growth spans from an estimated 0.7 million inhabitants in 1980, to 3.25 million in 2003 to 9.157 million in 2015 [8,9]. This rapid growth, primarily caused by the economic development due to oil sales and the ongoing repositioning of the country as a commerce and high-tech hub, has triggered a continuous influx of foreign workers and businesses. The infrastructure and urban development to support this growth has had to assume unprecedented scale.

Looking at the example of the Emirate of Dubai, first available statistics from 1955 show an urban area of only 3.2 km^2 in 1955, which grew to 606 km^2 in 2004, with further plans to extend the built-up area by another 501 km^2 by 2015 [10]. The urban development has adopted a cluster approach, with numerous mixed-use and residential clusters. In addition to housing developed for UAE nationals provided by the Department of Public Works (DPW), the clusters are typically developed by one of the major real estate developers, and sold as investment property or for personal use. Bagaeen [11] argues that the opening of the real estate market to the exterior, by allowing foreigners to buy freehold property in Dubai, has been the catalyst of this rampant expansion. In order to maximize profits, the major developers pursue economies of scale, and it is not uncommon to have hundreds (if not thousands) of homes built simultaneously in newly developed areas. In accordance, the residential villa stock has grown by over 300% from 2000 until 2009 [12].

Fig. 1. Typical single-family villa development in Dubai.

The growth in energy demand follows suit: in 1995 the demand was 25 TWh, in 2003 50 TWh, and in 2007 76 TWh [7], of which (2005 data) 45.9% was attributable to residential buildings and only 2.5% to commercial buildings [13]. Mokri et al. [6] report an annual increase in electricity demand of 10.8%.

A key factor contributing to this very high energy demand growth rate is that the cost of energy is kept artificially low through government subsidies. While the cost of production of a kWh of electricity is estimated to be $0.12 to $0.13, it is sold at an average rate of $0.04 per kWh in Abu Dhabi (with a further reduction for UAE nationals), and at a slab rate ranging from $0.06 to $ 0.10 per kWh in Dubai [5]. In addition to these low prices (and notwithstanding increasing efforts by the government to counteract this), there is a general unawareness of environmental and energetic considerations in the population [8]. These factors contribute to an average per-capita energy consumption that is nine times higher than the world's average energy consumption, four times higher than the EU's energy consumption, and two times higher than the US energy consumption [8]. These factors make the UAE the country with the highest ecological footprint in the world [5].

Thus an environment inclined to poor energy efficiency is created by:

- The need for rapid construction to accommodate rapid population growth
- The large-developer business model, where profit is maximized while keeping initial construction costs low [14]
- The artificially low cost of energy, reducing the perceived importance of operational cooling costs during the lifetime of the building
- The long time absence of any energy regulation forcing the implementation of insulation and efficiency measures
- The general unawareness of environmental concerns by the population

The UAE government is actively pursuing renewable energy technologies with the aim of addressing worldwide concerns regarding global warming and greenhouse gas emissions, and at the same time preparing an economic pillar for the country's growth beyond the oil years [6]. However, while renewable production has received much attention, energy conservation through effective construction is only slowly becoming mainstream through the development and implementation of adequate legislation.

This paper provides a review of work done specifically in the UAE on improving building energy efficiency by passive measures implemented to the building envelope in the planning phase or as retrofit, including radiative, convective and conductive heat transfer through walls, windows, roof, as well as energy efficient natural ventilation techniques. The review is geographically restricted to the UAE as its specific development challenges are directly tied to the distinct economic growth pattern of the country and the specific legislation implemented to address energy efficiency.

2. Energy efficiency regulation

The UAE is a young country that has experienced meteoric growth over the past decades. Due to this rapid growth, environmental considerations have lagged behind development needs, and only recently regulations have been put in place that address sustainability and energy consumption in buildings. In 2003, the Dubai Municipality introduced the Decree 66, which provides directives on insulation and glazing and, in 2007, Abu Dhabi followed suit by establishing the Urban Planning council, which subsequently developed and launched the ESTIDAMA Pearl building rating system in 2010. Dubai then introduced the Green Building Regulation [15] in 2011, which was mandatory for all government buildings and optional for non-government buildings, and then extended it to mandatory for all newly constructed buildings in 2014. Sharjah has also had thermal insulation regulation in place since 2003, that specifies insulation characteristics of walls, roof and glazing. The other Emirates (Ras Al Khaimah, Ajman, Fujairah, and Umm al-Quwain) either do not have energetic regulations in place, or are in the process of developing them [13]. Regardless of these developments, the USGBC LEED certification is perceived as prestigious and still pursued regularly, although it is arguable whether the application of a cost-of-energy based rating system developed for the US market by the USGBC is appropriate in the specific UAE climatic and constructive environment [7, 16].

There is clearly a rapid progression of emerging building energy efficiency regulations being implemented in response to the frantic growth of the UAE. These regulations differ from Emirate to Emirate, and are slowly becoming mandatory, however their execution is only becoming enforceable as the development and certification of implementation professionals increases [17]. In addition, these regulations focus on new buildings, and do not consider that the large building stock constructed during the past four decades is not energy efficient [7]. In the absence of binding regulations, a large number of UAE buildings have been mass-built by the major developers for sale to the end customer, with clear emphasis on minimizing the cost of construction so as to maximize profit while disregarding the operational aspect of the building life, a cost that the end user will assume. This has resulted in an energetically deficient building stock. AlNaqbi et al. [7] report that 27% of the Dubai residential building stock and 12.8% of the Sharjah residential building stock were completed pre-2003, and thus did not include any requirement for insulation. Abu Dhabi did not have an insulation requirement before 2010, and thus over 290,000 residential units (not including units built by DPW for UAE nationals) built since 1975 [7] did not have to incorporate any level of building insulation. A sample computational case study to assess the potential saving generated by retrofitting the existing poorly insulated villa stock to Pearl level results in over 37% reduction in cooling load [7]. This result is in agreement with Friess et al. [12] similar study for a Dubai villa, which results in a decrease in cooling load of 29.4% when full perimeter insulation is applied**.**

The buildings that mark the UAE's skylines have mostly been constructed prior to any of these regulations, and thus do not conform (or only marginally) to any regulations, and offer ample room for analysis and implementation of efficiency measures.

3. Building orientation and layout

Building orientation and layout has been shown to be of high importance in reducing building energy consumption in cold and hot climates. A number of factors beyond the building's constitutive elements affect a building's thermal performance, including climatological considerations, building shape and surrounding urban morphology. These factors dictate the amount of precipitation, thermal energy (direct and indirect) and wind (intensity and prevailing direction) that a building is exposed to. As such, early stage planning can be carried out to shape the urban development to best suit these influences, however this awareness is only slowly permeating the UAE building and planning community. In fact, deliberate energetic urban planning represents the best starting point for an energetically optimized urban environment and building composition, as shown by Taleb et al. [18]. They introduce the concept of urban parametric design and apply a genetic algorithm to optimize the layout of a Dubai mixed-use area to develop sustainable and healthy communities. Their initial results indicate possible energetic and ventilation improvements ranging from 8% to 30% over the as-built case; however such innovative strategies have not been considered in the layout of most UAE developments.

Aboulnaga et al. [19] also discuss the effect of urban patterns on building energy consumption by comparing four similar but differently oriented two-story residential buildings in Al Ain. Based on their results, the authors recommend inclusion of energetic considerations in the development of urban patterns. This recommendation is justified by reported energy savings of up to 55% accomplished by limiting fenestration to only two elevations, and restricting the window to surface area ratio to about 1:6. The MASDAR development in Abu Dhabi represents a singular exponent of the application of best energetic practices at all levels, as the entire development is conceived with sustainability and energetic considerations as focal areas, however little quantitative experimental confirmation of the projected energetic savings [20, 21] has been reported in the literature.

The next level of geometric optimization occurs at the individual building scale, and consists of configuring the building's shape and volume distribution in an optimal manner. These considerations, often constrained by the specific characteristics of the planned building and the size, shape and orientation of the building plot, can be quite restrictive in the case of high-rise office and commercial buildings. In these buildings, space needs to be maximized for a given footprint, thus often resulting in “standard” rectangular-shaped office towers [22] that leave only limited room for layout optimization (however, some departures to this model exist, and successfully leverage shape effects to improve natural ventilation [23]). In accordance, low-rise residential buildings and villas offer the highest shape flexibility and thus best potential for energetic shape optimization, and constitute the subject of study for the bulk of the work reviewed in this context.

The directionality of solar radiation due to the sun’s path implies that there are favored directions in which the sun will penetrate deeper into a building through the glazing, thereby increasing the solar heat gain. In the low latitudes of the UAE, sunlight will penetrate deepest into buildings on their western and eastern facades (low sun position at sunrise and sunset) in the summer, and in the western and eastern as well as the southern elevations in winter. Thus restricting fenestration on the exposed sides and/or applying solar control measures to the glazing will improve thermal performance of the envelope. The new green building legislations that are currently being implemented incorporate this insight by prescribing maximum window areas for the different orientations and appropriate solar-control glazing [15]. While specific improvements in glazing and shading are presented in a later section, the building layout can also foster solar control and improved ventilation. The architectural feature of a central courtyard is deeply rooted in the traditional Middle Eastern architecture, and positive results have been reported by a number of UAE based studies.

The courtyard introduces two mechanisms to aid in the cooling of the home. First, fenestration can be concentrated towards the courtyard [24]. This strategy increases shading, and provides less directional solar heat gain sensitivity. Second, the courtyard can be utilized in a number of convective cooling strategies, such as utilizing fountains for evaporative cooling, increasing natural ventilation by improved cross flow and stack effect, and even coupling the ventilation strategy with a wind catcher or wind tower.

Al-Sallal [25], in his comprehensive design study of a sustainable house in the Abu Dhabi desert that includes many of the passive cooling strategies of the courtyard, compared the energetic performance of a house that incorporates a courtyard with one that reflects the typical square form. Keeping all other variables (floor area, shading, glazing, wall insulation levels, etc.) the same, the performance of the courtyard house reduced the cooling energy by 4%, the fan energy by 2%, and the lighting and equipment energy by 21%, resulting in a total electric energy savings of 8%.

Al Masri et al. [24] investigated the inclusion of a central courtyard in a medium-rise residential building in Al Ain. The base building (no courtyard) and the courtyard building retain the same floor area and volume, but the courtyard building has a 47.2% higher external wall area. While the opening area remains unchanged, it follows a different distribution as openings in the courtyard model are primarily directed to the courtyard. Such an arrangement results in a 54.7% reduction in solar gain, as most openings are shaded and located in the controlled courtyard. However, the larger wall area implies an increase in conduction gains through the walls of 54.15%. Upon combining these results, a net reduction of 6.9% in total energy consumption is achieved due to the purely geometrical introduction of the courtyard (all other variables beyond heat gains through the walls and windows are kept constant).

From these results it becomes apparent that courtyards represent an effective architectural component that not only addresses energy savings, but also one that is aligned with the cultural and historic development of the UAE.

4. Wall and roof treatment

Wall insulation levels become an important parameter in energy conservation in residential villas, as window-to-wall ratios are lower than in office high-rises, and more heat is transmitted through the opaque portions of the building envelope. As such, most studies address low-rise villas and apartment buildings. The heat loss in buildings of this type can represent up to 30% of the total building's cooling load [25,26], and thus improving the insulation becomes a critical driver to attain higher energetic efficiency.

In recognition of this importance, all energy regulations introduced in the UAE since 2003 prescribe maximum U-values. However, currently the only regulated Emirates are Dubai and Abu Dhabi, where since 2014 the Dubai Green Building Regulations limit U-values for the roof and walls to a maximum of 0.3 W/m^2K and 0.57 W/m^2K respectively, and the Estidama PEARL code applied in Abu Dhabi, which prescribes (at its lowest rating) maxima for roof and wall U-values of 0.14 W/m^2K, and 0.32 W/m^2K respectively [27].

There are two primary mechanisms that contribute to heat transmission through opaque building enclosures: first, the conduction through the walls due to the temperature difference from inside to outside ambient temperature, and second, additional conduction through the walls due to radiative solar heating of the outside surface of the walls. The mitigation approaches for both mechanisms differ, as the first requires increased insulation, and the second implies decreasing the amount of solar energy absorbed by the outer surface of the wall.

Transmission by conduction is addressed by increasing the wall's resistance to conducting heat. In the context of the UAE typical mass-wall or barrier-wall construction that utilizes reinforced concrete structure and concrete block, this reduction of conduction losses primarily takes on the form of thermal bridge mitigation and increased application of insulation materials.

Friess et al. [12] present an experimentally-calibrated computational study on the role of thermal bridges in the energetic efficiency of residential villas in Dubai. Their analysis notes that the villa, constructed under the Dubai Municipality Directive 66 that prescribes a maximum U-value to be used for the concrete block employed (0.57 W/m^2K), does not specify a maximum U-value for the reinforced concrete structure (the study was carried out in 2011, prior to the implementation of the Dubai Green Building Regulations, which include a qualitative provision addressing thermal bridges). Upon modeling the villa, it was noted that only 24% of the perimeter area is composed of the insulated block (U value of 0.523 W/m^2K), while up to 53% of the perimeter consists of the reinforced concrete structure of the home, which remains un-insulated (U-value of 2.398 W/m^2K). A number of insulation variations were computed, observing both the effect of insulating the thermal bridges to the same standard (50 mm of EPS) than the concrete block (resulting energy savings of 23.3% over the as-built case), to a sensitivity analysis of different insulation thicknesses over a hypothetical un-insulated case (resulting in a 26.8% reduction of the energy consumption for a 50 mm insulation, and a further 7.4% reduction when increasing the insulation thickness from 50 mm to 160 mm). The results underline the importance of adding insulation to the entire opaque envelope, however also show that diminishing returns are obtained upon increasing the insulation thickness beyond a minimum threshold.

In a follow-on study, Rakhshan et al. [28] examined the environmental impact of the increased insulation levels for the same villa, and report that the sustainability cost of adding the insulation is small in comparison to the operational energy savings and GHG emissions.

Radhi [26] conducted a study to assess the impact of using AAC blocks on the energy performance of UAE residential buildings. In this study, the author compares 5 different insulation systems in order to ascertain the effectiveness of AAC blocks as a building/wall insulation material for residential applications. Energetically, 200 mm AAC block is superior to similar wall structures composed of sand-cement block and red clay brick, and only slightly worse (0.05%) than 200 mm sand cement block with 25 mm- 50 mm EPS insulation, however financially it only becomes viable in Sharjah, where the electricity costs are 10 times those of Abu Dhabi (0.013$/kWh in Abu Dhabi vs. 0.13$/kWh in Sharjah, as reported by Radhi [26]). In Abu Dhabi the subsidized electric costs imply that the better-insulated solution is more expensive over the lifetime of the building. The author also calculates the CO_2 savings due to the application of AAC. According to this study, it was found that using AAC can reduce energy consumption in residential buildings by 7%. Also, a saving of 350 kg of CO_2 per square meter of AAC wall is achievable.

Radhi [13] presents a study that projects the implications of global warming on the energy consumption and CO_2 production of the UAE residential sector, analyzing the effectiveness of a collection of measures (including thermal insulation, thermal mass, shading, window to wall ratio, and optimized glazing system) toward mitigating the projected consumption and emission rise. The subject of study was a residential building located in Al Ain, where the author decreased the U-Value of the walls from 2.32 W/m^{2}K to 0.3 W/m^{2}K by adding 35 mm of polystyrene, and similarly for the roof from 0.6 W/m^{2}K to 0.2 W/m^{2}K. This yielded in a 19.3% reduction of cooling energy. Then the author introduced thermal mass (by using 250 mm heavy weight concrete block in place of the original 150 mm lightweight concrete block), in turn decreasing the cooling energy by 13.4%. Results indicate that, among all measures explored in this work (insulation, thermal mass, shading, glazing, and window area), thermal insulation and thermal mass are most effective at decreasing cooling load and overall energy consumption of residential buildings.

Increasing thermal mass in building walls has the effect of time-shifting heat loads; the envelope temperature lags behind the ambient temperature. While no direct studies are reported from within the UAE, studies in similar environments (Saudi Arabia) confirm that increased thermal mass decreases energy consumption: Al Sanea et al. [29] have shown that increased thermal mass is beneficial by decreasing peak transmission loads, and by reducing heating transmission loads through the walls in particular during the moderate months. An important criterion is that insulation should be placed on the outside, so as to minimize the heating of the thermal mass.

Afshari et al. [5] examine the effect of increasing opaque partition insulation in their study of a fifteen-story mixed-use building in Abu Dhabi, reporting a 2.6% annual cooling load reduction upon increasing insulation from a U-value of 1.71 W/m^{2}K to a U-value of 0.324 W/m^{2}K (through the addition of 80 mm of EPS). This low reduction is due to a relatively small opaque partition external area (the building’s window-to-wall ratio is 70).

Al Masri [24] presents a comprehensive computational parametric study on the integration of a courtyard into a typical Dubai mid-rise residential building, by quantifying energy savings due to the courtyard form, as well as the effect of increasing the wall thickness, various insulation materials, and increasing wall insulation thickness. The authors explore different thermal masses and different thermal conductivities of the perimeter walls. Results indicate that the building is insensitive to thermal mass, as a decrease from the base case (thickness 25 cm) to 15 cm only generates increased energy consumption of 0.6%, while an increase to 40 cm results in a reduction of 0.9%. In all cases the insulation thickness remained constant at 5 cm. The authors also carry out a comparative between five different insulation materials, and conclude that their respective effectiveness is a function of their thermal conductivity. Upon varying the insulation thickness about the base case (5 cm thick insulation) to 10 cm and subsequently to 2.5 cm, the authors report a 3.6% decrease in energy consumption to an increase of 5.44% of energy consumption respectively. These results indicate similar orders of magnitude to the results of Friess et al. [12], where a decrease of energy consumption of 6.5% is reported upon increasing the insulation from 5 cm to 16 cm.

Table 1 Comparative results of building insulation studies reviewed

Author	Type	Location	Change (U value in W/m2K)	Result (EUI in kWh/m2a)
Friess et al. [12]	Villa	Dubai	Insulating the thermal bridges (54% of enclosure): Adding 50 mm EPS (U from 2.398 to 0.600) Insulating full perimeter: No insulation to 50 mm EPS (U from 2.398 to 0.600) 50 mm insulation to 160 mm EPS (U from 0.600 to 0.226)	23.3% electrical consumption reduction EUI from 220 to 161 (26.8% reduction) EUI from 161 to 149 (7.4% reduction)
Radhi [26]	Villa	Al Ain	Change in U value: Walls U from 2.32 to 0.3 Roof U from 0.6 to 0.2 Change in Thermal Mass: Concrete thickness from 150 mm to 250 mm	19.3% cooling energy reduction 13.4% cooling energy reduction
Radhi [13]	Villa	Al Ain	Change Sandstone (U = 1.64) to AAC (U = 0.16)	7% total energy consumption reduction
Afshari et al. [5]	15 story office	Abu Dhabi	U from 1.71 to 0.324 Observation: building has high window to wall ratio of 0.7	2.6 % cooling energy reduction
Al Masri et al. [24]	Villa	Abu Dhabi	Cellular Polyurethane insulation thickness from: 50 mm (base case) to 25 mm 50 mm to 100 mm Thermal mass from: 250 mm to 150 mm 250 mm to 400 mm	5.44% energy consumption increase 3.6 % energy consumption decrease 0.6% energy consumption increase 0.9% energy consumption reduction

Table 1 shows a summary of the results discussed above. It demonstrates that the addition of insulation is critical to decrease the energy consumption of buildings in the UAE, as all reviewed studies indicate improvements upon adding insulation or increasing the thickness of the insulation. Results indicate that any thickness is effective, with diminishing results as the thicknesses increase. In particular thermal bridges, if left untreated, can represent a large un-insulated fraction of the building, effectively negating any insulating effect prescribed by the building code. Thermal mass follows the same trend, however both studies that address its effectiveness report improvements that differ by an order of magnitude. Additional work indicates that in order for the thermal mass to provide optimal results, the insulation should be placed on the outside of the wall.

5. Wall and roof solar absorption

Solar absorption on external surfaces has a significant impact on heating of the wall beyond the ambient temperature, and thus will increase conduction through the wall and directly impact the cooling loads.

In recognition of this effect and since 2014, the Dubai Green Building Regulations mandate for all new buildings in the Emirate, that at least 75% of the area of externally painted walls have a minimum light reflective value of 45%, and a minimum Solar Reflective Index of greater than 78 for flat and low sloped roofs. Further, the use of green roofs is rewarded [15].

Radhi [30] evaluated the impact of different wall cladding systems on direct and indirect CO_2 emission of a three-story academic building in Al Ain. The base-case building has an overall area of 4500 m^2 with set-points of 22°C to 24°C in summer and 20°C to 22°C in winter. The window-to-wall ratio varies between 0.24 and 0.37 depending on the façade orientation. Operational energy and CO_2 is modeled using the Design Builder front-end to EnergyPlus. Studied systems in this paper include stucco, masonry veneer, aluminum siding, vinyl siding, and exterior insulation and finish systems (EFIS). While primarily focusing on the optimization of the cladding systems with regards to CO_2 emissions, the study specifically reports on the sensitivity of the cooling loads to the absorption coefficient of the outside surface. Results indicate that the heating and cooling energy utilized by the building is inversely proportional to the absorption coefficient of the outside cladding material. While these results could be caused by the differing U-value for each cladding system (where again a mass-wall utilizing EFIS displays the lowest U of 0.523 W/m^2K, and masonry the highest U of 1.513 W/m^2K), the authors present sensitivity results that isolate the impact of the absorption coefficient onto the heating and cooling loads: the cooling load required using EFIS (with a low absorption coefficient of 0.17) as a cladding system is about 126.5 kWh/m^2, this increases to 129.0 kWh/m^2 in the case of masonry veneer (with the worst absorption coefficient of 0.55). This corresponds to a difference of 1.9% in the heating and cooling load.

Taleb [31] includes a reflective white poly insulation with an R-value of 15.76 m^2K/W in a study of a typical Dubai villa, and includes a reflective coating with a 61% reflection, however does not report the savings caused by this specific retrofit, rather only reports the overall effect of all measures (including evaporative cooling, window retrofit, natural ventilation and external louvers) to be 23.6% savings over the as-built case.

K.A. Al-Sallal et al. [25] designed a sustainable house in the desert of Abu Dhabi using Estidama Guidelines and rating methods along with referring to other standards or less formal documents such as LEED Homes or Resolution 66 of Dubai Municipality (DM). The authors implement the U-value requirements for the envelope as per DM Resolution 66 (0.57 W/m^2K for walls, and 0.44 W/m^2K for floor slabs and roof), which resulted in an energy reduction of up to 40% over a reference case that incorporates the material assemblies typically found in an Emirati house (albeit without specifying these or the associated transmittance). However, the authors present quantitative energy savings attributed to shading of the perimeter, thereby avoiding direct and reflected solar heating of the walls. These landscaping measures reduced the thermal load through the walls by 18.4% (and 31.4% through the windows), materializing in an overall reduction of cooling energy of 6% and fan energy by 8%.

M. Haggag et al. [32] introduced a green wall to decrease heat gain through the envelope of a school building in Al Ain. Photovoltaic panels were employed to generate the electricity for the lighting and irrigation system of the green wall. In this experimental study the green façade was examined in situ to assess its performance in hot and arid climate of Al Ain. Two identical east facing classrooms, one with the green wall and the other one bare, were selected. The measurements show that the green façade can regulate the shaded wall external temperature by 5˚C to 13˚C during the day. While during the night the green wall acts like a thermal insulation through trapping heat inside, the results show that the internal wall temperature of the green façade is always lower than that of the bare wall which results in continuous energy saving throughout the day.

Taleb [31] includes a green roof as a passive cooling strategy in the performance model of a Dubai villa, however does not provide details on the type of green roof utilized or the specific performance improvement due to the green roof.

Table 2 Comparative results of studies addressing solar absorption of opaque building enclosures.

Author	Type	Location	Change	Result
Radhi [30]	3 story academic building	Al-Ain	Changing wall cladding systems: Stucco, Masonry veneer, Aluminum siding, Vinyl siding, Exterior Insulation and Finish systems (EFIS)	EUI is proportional to absorption coefficient: EFIS (abs. coef. 0.17) results in EUI of 126.5 kWh/m^2, vs. masonry veneer (abs. coef. 0.55) EUI of 129.0 kWh/m^2 (1.9% reduced heating and cooling load)
Taleb [31]	Villa	Dubai	Use of reflective white poly insulation with an R value of 15.76 m^2 K/W with 61% reflection	Energy saving not specified
Al-Sallal et al. [25]	Villa	Abu Dhabi	Use of landscaping measures such as Palm trees, ornamental trees and aqueous plants as well as grass ground cover to avoid direct and reflected solar heating of the walls	18.4% reduction in thermal loads through walls and 31.4% through windows 6% saving in cooling energy and 8% saving in fan energy
M. Haggag et al. [32]	School	Al Ain	Introduction of green wall	Reduction of external wall temperature by 5˚C to 13˚C during the day

The above results indicate that reducing solar heating of the outer surface of the wall contributes to cooling energy savings. The two strategies reported include using exterior wall surfaces that boast a lower solar absorption coefficient (with reported cooling load savings of up to 1.9%), as well as the use of vegetation both as shade generators detached from the building, and for greening the roof and walls. The latter has been shown to be effective in a number of scenarios and additionally reduces the solar heat gain through the windows [33], while the former introduces the advantage of additional evaporative cooling on the structure, albeit at a higher level of constructive complexity, and potentially higher water use.

6. Windows

Building glazing fulfills a twofold mission: it allows light in for occupant comfort, but also provides a physical barrier to the outdoor conditions. Daylight in the workplace is an important contributor to occupant wellbeing and reduces lighting electricity demand; as such, increasing window area is a common practice. However, and of particular importance in the UAE due to the local very high solar irradiance [6], excessive direct sunlight causes glare, which in turn negatively affects occupant wellbeing. To counteract glare, measures have to be taken to transform direct sunlight into indirect and ideally diffuse light, and this is often accomplished by either exterior or interior shading. The second mission of window glazing is one of physical barrier, which in the thermal context implies reducing heat transmission from the hotter outside environment to the cooled inside environment. This heat transmission takes on three primary forms for closed windows: first, conduction through the glass, second is solar heat gain by radiative transmission through the glass, and a third mechanism is conduction through the window frame. The latter, and due to the low area and often included thermal break in window frames, is often not as significant.

The practical considerations described above are not the only drivers that come into consideration in office buildings, but aesthetic and architectural standards often dictate the appearance of the buildings. In particular, full glass enclosures have become the norm worldwide for office towers [34]. The reason for this preference is that daylighting represents an optimal strategy to enhance occupant wellbeing and decreases lighting cost, which can be (in more moderate climates) the single largest energy consumer of the building. However, in the climatic and solar context of the UAE, daylighting can produce adverse effects of excessive light and glare.

Aboulnaga [34] reports that Dubai receives solar irradiance of up to 850 W/m^2 during the summer, with associated sky illuminance levels ranging from 75,000 lx to 107,500 lx. These levels far exceed the optimal indoor daylighting levels that range from 300 lx – 2000 lx and thus, unless great care is taken in glazing selection and shading, the light levels become excessive and can result in a negative effect on occupant comfort and solar heat gain. Al-Sallal [35] reports similar findings of 3-4 times the daylighting levels of 2000 lx recommended for architectural studios and task lighting, and Mokri et al. [6] confirm these findings of very high irradiance.

In recognition of this effect, the Dubai Green Building Regulations implemented in 2014 now require at least 50% of the glazed areas to be on the north side of the building, and require environmental treatment of the South and West glazed areas. In addition, minimum glazing requirements (for over 60% glazed buildings) demand a maximum U value of 1.9 W/m^{2}K, a maximum shading coefficient of 0.25, and a minimum light transmittance of 0.1 [15].

Thus the trend of fully glazing office towers seems to not be directly transportable to the UAE without implementing shading measures that reduce glare and excessive lighting levels in the daylit zones (about 2.5 times the height of the opening away from the window in side-lit scenarios, as are common in office towers), as well as limiting solar heat gain to reduce cooling requirements; Al-Sallal [36] states that "designing buildings based on ready-made foreign standards and past experiences that do not necessarily fit into the desert environment". Reducing the amount of light transmission in fully glazed façades is typically accomplished using external and internal shading, window films, and high performance glazing.

Aboulnaga [34] surveys the glazing solutions of 15 office buildings in Dubai as to their light transmittance, reflection, shading coefficient (SC), and relative heat gain, by splitting them into three categories (high, intermediate and low performance). High performance buildings were defined as those with glazing having a shading coefficient of 0.12-0.29 (significantly below the 0.35 limit established by the Dubai Municipality); intermediate performance buildings were those with a SC between 0.31-0.35, and low performance buildings with SC ranging from 0.36-0.46. The medium-to-low performance buildings have required a number of retrofits (such as external louvers) and occupant solutions such as venetian blinds and even aluminum foil to control the excessive heat and glare. A subsequent computational case study of daylighting levels using a building from the intermediate group reveals that the use of clear glass in unobstructed buildings can generate daylighting levels of more than 10,000 lx. As a result of his work, Aboulnaga recommends a shading coefficient of less than 0.2, and discourages large glazed areas.

Al-Sallal contributes work on daylighting issues in classrooms and in the Architectural Engineering Building at UAE University [33,36]. The author discusses the effectiveness of shade trees to improve lighting distribution and quality in classrooms, as many are inappropriately lit allowing excessive direct sunlight to enter the space. The resulting high brightness contrast and acute glare generates occupant discomfort to the extent that windows are covered with paper or drapes, thus negating the intended positive daylighting effects. Al-Sallal [33] also reports on the effectiveness of shading trees in blocking direct sunlight but generating reflected sunlight (diffuse light without glare), with results supporting the use of Ghaf or Neem trees (evergreen) to improve the quality of natural lighting, as only a minor increase in electrical lighting is needed to illuminate the back spaces.

Hammad et al. [37] address the solar heat gain through glazing by incorporating dynamic external louvers as shading devices in an office building. Their computational study analyzes the effect of static and dynamic external louvers when added to a fully glazed office suite with glazing corresponding to the low performance building category of AboulNaga's study (SC of 0.41 and 0.76 with a U value of 1.95 W/m^2K). The maximum reduction of total energy consumption ranges between 28% and 34% when utilized in conjunction with interior light dimming control (keeping the interior ambient illuminance levels at 500 lux). The use of static louvers was marginally less effective than the dynamic case. The louvers were least effective on the east and west facades, where light dimming technology is sufficient. In contrast to Hammad's work, Al-Sallal [36] argues that due to increased maintenance requirements in the high dust UAE environment, exterior dynamic shading systems are not recommended, favoring systems located in the glass cavity or within a double façade.

Radhi et al. [38] analyzed the impact of multiple façades systems on the overall energy consumption of fully glazed buildings. They modeled the Architectural Engineering Building in UAE University using Building Energy Simulation software coupled with RANS CFD to analyze the airflow between the façades. The results quantify the energy usage differences between a single façade and a double façade system to be between 17% and 20% on a sunny day.

Afshari et al. [5] analyze a series of retrofit measures toward their energetic and sustainability impact by modeling a 15 story mixed-use office type building with 70% window to wall ratio with continuous horizontal glazing with a U value of 2.4 W/m^2K and a solar heat gain coefficient of 0.36. Two types of glazing retrofits are applied (double pane, low-gain, low-e insulated frame and either Argon filled or Air filled, resulting in U values of 1.47 W/m^2K and 1.7 W/m^2K respectively and a SHGC of 0.3 for both), with results indicating a peak load reduction of up to 4.2%, and an annual cooling load reduction of up to 4.6%.

Friess et al. [12] discuss the role of improved fenestration in the overall energetic consumption of a UAE villa in the context of envelope insulation specific work. They quantify the window area of the UAE single family home used in their study to be 21%, with sliding windows having thermal control double pane glass (24mm) with a U value of 1.8 W/m^2K, a SHGC of 0.37 with visible transmission of 41%. Only limited exterior shading is used. Given the low window-to-wall ratio and the residential use, daylighting is not a primary driver and improving the fenestration has little effect on the overall energy consumption; the authors quantify that replacing the glazing with highly reflective, low-emissivity triple glazing generates an improvement of 4.6% over the base case.

AboulNaga [19] presents a case study located in the city of Al Ain, where he analyzes four two-story residential buildings integrated into the urban grid, but oriented differently. Results indicate for the case studies reported (building sites oriented at 30° North East), that limiting windows to only two orientations at 60° North-East has the potential to reduce energy consumption by up to 55% over the existing more regular window distribution and single pane glazing.

Taleb et al. [31] incorporate a change in glazing (from single glazing to Argon filled double glazing with solar control film, resulting in a SHGC of 0.17) to their overall analysis of the effect of 8 passive cooling measures on a villa in Dubai, and report that the combined effect of all measures reduces demand by 23.6%. However, the specific effect of the glazing change alone is not reported.

Al Masri et al. [24], and in the context of the study of courtyard integration into mid-rise residential buildings, also examines the energetic effect of improving glazing. The glass type is varied from single glazing, to double glazing low-e, to triple glazing low-e, and thus focuses primarily on heat conduction through the windows, and not solar heat gain. The reference model incorporates double low-e glazing, and results indicate that single glazing increases energy consumption by 12.31%, while choosing low-e triple glazing only improves energy consumption by 2.32% over the base case. These results are obtained in the framework of a low opening to wall ratio of 14%, and without attempting to decrease the SHGC of the glazing using reflective coatings.

In a design study for sustainable house in the Abu Dhabi desert [25], Al-Sallal utilizes vegetation to reduce direct and reflected solar heat gain, attaining a 6.6% reduction in the annual cooling load. Further work by the same author includes model testing of the UAE University Architectural Engineering Building [35] addresses adding a reflective light shelf to increase backspace illumination level, which only demonstrates seasonal effectiveness, as well as confirming the positive effect of adding translucent layers to the skylights.

Table 3 Comparative results of glazing and shading studies reviewed.

Author	Location	Type	Actions	Results
Radhi et al. [38]	Al Ain	University building (100% glazing)	CFD and building energy simulation of impact of climate interactive façade systems	17% to 20% reduction in cooling energy
Afshari et al. [5]	Abu Dhabi	15 story mixed-use (70% glazed)	Improve glazing from U 2.4 and SHGC 0.36 to: U 1.7, SHGC 0.3 U 1.47, SHGC 0.3	3.5% annual cooling load reduction (3.6% peak) 4.6% annual cooling load reduction (4.2% peak)
Hammad et al.[37]	Abu Dhabi	Office (60% glazed)	Addition of external dynamic louvers in combination with interior lighting control	28% to 34% reduction of total annual energy consumption
Friess et al. [12]	Dubai	Villa (21% glazed)	Change double glazing (SHGC 0.37) to high reflectivity, low-e triple glazing	Up to 4.6% reduction in annual energy consumption
Aboulnaga et al. [19]	Al Ain	Two story residential	Analyzes optimal positioning and window area	Up to 55% reduction in annual energy use by limiting windows to two elevations (60 North-East) and 10%-20% window to wall ratio
Taleb [31]	Dubai	Villa	As part of eight passive cooling strategies louvers and glazing change from single to double low-e Air filled were modeled	Reduction of 23.6% of all measures combined (no individual result due to glazing and window treatment given)
Al Masri et al.[24]	Dubai	Mid-rise residential (14% glazed)	As part of a study regarding integration of a courtyard, changes in glazing were analyzed: Changing from single pane to double pane low-e Changing from double pane low-e to triple pane low-e	12.31% reduction of total energy consumption

				2.32% reduction of total energy consumption
Al-Sallal et al. [25]	Abu Dhabi	Villa	A range of vegetation and landscaping based shading measures were taken in a study of a sustainable house	6.6% reduction in total energy consumption due to shading

The above results indicate that appropriate fenestration levels and glazing choices constitute a critical factor for energy efficiency in buildings in the UAE, in particular in mixed-use and office buildings, with lower sensitivity in villas as they boast significantly lower window-to-wall ratios and less dependence on daylighting for their use. The absence of regulation and improperly implemented building trends from other parts of the world have resulted in buildings with excessive glazing and poor choice of glass, in turn resulting in very high solar heat gain through the windows, improper daylighting levels and high glare conditions, as well as significantly increased cooling energy demand.

7. Natural ventilation

Natural ventilation has the potential to reduce energy consumption by convectively cooling the building's interior, while at the same time contributing to good indoor air quality. The concept relies on an air exchange with the outside that is typically driven by pressure and temperature differences, and that does not rely on mechanical systems.

Perhaps the most characteristic exponent of natural ventilation in traditional Arab architecture is the wind tower, or wind catcher (Fig. 2). The wind tower takes advantage of the pressure differences generated by wind around a building, and generates a cross-flow in the building by positioning the inlet in a high pressure area, and the outlet in a low pressure area [39]. If there is no wind, the wind catcher utilizes the stack effect (buoyancy due to temperature differences at different elevations), and the inlet acts as outlet for the stack, however research has shown that wind-driven ventilation in a wind catcher will provide 76% more ventilation than buoyancy driven ventilation [39]. To enhance the ventilation rate, a wind catcher may be combined with a separate solar chimney.

Fig. 2. Badgir Wind tower in Dubai.

Hughes et al. [39] provides a comprehensive review of the development and building integration of wind towers. Important design considerations are height (as wind speed will increase with elevation), position (to minimize the effect of surrounding structures), and alignment with the prevailing wind direction. In order to be located in the highest-pressure area, the wind catcher opening should be at the windward side of the roof for a location with a clearly prevailing wind direction, or at the center if multi-directional wind is the norm. The height is chosen to ensure that rooftop turbulence does not affect the air inlet. In addition, in the hot and dry areas of the Gulf, added height will also decrease the dust and pollution intake.

Wind catchers may be unidirectional or multidirectional, with partitions to create multiple shafts, where only the windward one will be active as inlet, and the other shafts will be functioning as outlet. Rectangular cross sections show higher performance than circular cross sections. While multiple shafts decrease the overall airflow, such a wind catcher will be less sensitive to changing wind conditions. In particular the four sided Badgir (Fig. 2), which was developed in Iran in the 9th century AD [40], has found widespread application in the UAE [41,42].

While the traditional wind catcher does not incorporate any active cooling, their effectiveness is limited in areas with high outdoor temperatures. In these hot arid regions cooling devices can be integrated into the wind catcher design, an example being the incorporation of evaporative cooling pads, columns, or underground water streams over which the air passes before entering the building [39].

Wind towers are also often applied in conjunction with a courtyard to further enhance cross ventilation [25], which represents another typical element of Middle Eastern traditional architecture.

There is ample literature on the effectiveness of wind towers, as well as a number of specific examples of their application in Iran, however in the UAE, and in the context of modern construction developments, the wind tower has largely remained an aesthetic element mimicking vernacular architecture [42], but without its intended functionality (Fig. 3). Only in very recent years and due to the increased awareness of energy efficiency, has the wind tower received renewed attention as a functional building element in the UAE.

Fig. 3. Villa development in Abu Dhabi incorporating fake wind towers.

A UAE based computational example is provided by Taleb [31]. The author analyzes a number of passive cooling strategies in the context of a newly constructed villa in Dubai, modeling the natural ventilation effect of a wind catcher and cross-ventilation. The wind catcher is computationally modeled at a height of 10 meters in order to remain outside of the rooftop turbulence field, and its louvered opening points into the prevailing wind direction in order to route airflow into the building. In the context of this study, enhanced crossflow was achieved by opening the terraces and windows in the computational model. The results presented do not single out the performance of the natural ventilation strategies, but combine the savings for all eight energy efficiency modifications considered (light color with high reflection, indirect radiant cooling, evaporative cooling using a fountain, improved insulation, green roofing, the natural ventilation techniques described, as well as exterior louver shading and double glazing). The overall energy savings reported were 23.6% over the original building.

Al-Sallal [25] introduces the wind tower and courtyard elements of Emirati vernacular architecture in the design of a sustainable house in the Abu Dhabi desert. The authors incorporate two wind towers into the design, functioning as wind catchers during cool nights and as solar chimneys during daytime to evacuate excess heat from the home. The results presented include a number of other passive measures, without attributing specific results to each measure; however the collective effect indicates savings potential of 59% in greenhouse gas emissions and utility bill over the base case (a similar home built according to Dubai Municipality Decree 66 regulations).

The above studies show that there is increased interest in the wind tower as a functional energy efficiency element, however their implementation in the UAE to date remains at exploratory levels in isolated design studies. Possible barriers for implementation can be found in the perceived higher indoor air temperature variations and quality (dust-loading) that wind towers provide over normal air conditioning, the more rigid architectural layout constraints that effective wind towers require, and higher construction costs coupled with low and subsidized electricity costs. However, emerging energy efficiency regulation coupled with increased appreciation of the integration of traditional building elements that reinforce historic identity in architectural solutions may support a more widespread implementation of wind towers.

Additional natural ventilation strategies include generating cross-flow through the windows, mixed mode ventilation, as well as using solar chimneys and the stack effect to enhance airflow into the building.

Taleb [43] examines the natural ventilation levels attained in a Dubai villa in 5 scenarios, with different durations of ventilating the building by opening the windows during the winter months, and provides computational results regarding the energy consumption and temperature fluctuations for each case over the base case (where the AC operates year round, with no natural ventilation). Results indicate that all scenarios including natural ventilation offer energy savings over the base case, however with different degrees of temperature deviations from the envisioned set point of 22 °C. In particular, operating the AC only during the summer months and utilizing natural ventilation in winter offers up to 30% energy savings over that base case. An additional result was that the savings in the different scenarios remain insensitive to a building rotation by 45 degrees from its original orientation.

Due to the high solar irradiance, solar chimneys represent a viable ventilation technique in the UAE. Solar chimneys function on the basis of the stack effect, generating temperature driven buoyancy convective flows. In order to maximize the natural convection, the solar chimney needs to heat the air as much as possible, and thus typically solar collectors are included to heat the air.

Aboulnaga [44] presents a theoretical analysis of the optimum geometry of an inclined roof solar chimney with absorber plate coupled with an evaporative cooling cavity at the inlet in a two story residential building in Al Ain. Results indicate maximum volume flow rates of 0.81 m^3/s at an average solar radiation of 850 W/m^2. A follow-on study by the same author [45] further extends the theoretical optimization of the chimney configuration by adding a wall portion (wall-roof solar chimney) yielding airflow rates of 2.3 m^3/s, resulting in up to 26 air changes per hour for a single family house in Al Ain. The authors suggest that night time ventilation at this rate is sufficient to provide the required cooling for a heavy residential building [45].

The above studies show that natural ventilation has been studied and implemented in the UAE primarily in low-rise residential units. High-rise and mixed-use buildings generally rely on air conditioning year round to maintain appropriate indoor conditions, and do not include owner-operated or wind or stack effect driven ventilation (studies report that using passive natural ventilation in office buildings has been found to be insufficient in order to maintain thermal comfort [46]). However, combining active systems with passive ventilation strategies can take advantage of mixed-mode ventilation, which implies supplementing the active systems with outside air when the exterior conditions are suitable (often winter time or nighttime conditions).

While no reports regarding buildings in the UAE were available, Ezzeldin et al. [46] explores variations in mixed-mode ventilation and low energy cooling systems in office buildings in a number of arid climates, one of which (Manama, Bahrain) closely resembles the UAE conditions of average temperature and humidity. An intermediate single story of a building optimized for best annual plant demand and employing three different active system configurations (VAV, CAV, and CAV combined with radiant cooling) was used as the base case in the study, and five variations of cooling strategies including natural ventilation were assessed: simple mixed-mode during work hours, mixed-mode during work hours with a nighttime convective cooling strategy, mixed-mode combined with evaporative cooling, mixed-mode with radiant cooling coupled with a cooling tower, and mixed-mode with radiant cooling coupled to borehole heat exchangers. While a heat balance based computational model was used for the fully active system base cases, an adaptive computational model was employed for the mixed-mode cases, including the expectation of adaptive occupant behavior and acceptance of a wider range of room comfort conditions, which implied that the set points for the mixed-mode systems could be higher that the set points for the active systems. Results indicate that:

- Due to high ground temperatures, borehole heat exchangers coupled with radiant cooling are not feasible in climates similar to the UAE
- Evaporative cooling systems show significant energy savings, and including the energetic cost of desalinating the water required only increasing the total system energy consumption by 5%
- Using simple mixed-mode systems over base case VAV systems results in plant energy savings of between 35% and 63%
- Using night ventilation in addition to mixed mode ventilation further increased energy savings to 56% to 79% over the VAV base case
- Using mixed-mode ventilation in conjunction with a cooling tower for the slab radiant cooling (no night ventilation) resulted in energy savings from 55% to 73% over the VAV base case, and savings of up to 25% over the simple daytime mixed-mode system

The results show a very high potential for variations of mixed-mode ventilation in arid climates. However, and due to the significantly wider range of internal set points adopted in the adaptive mixed-mode model than in the VAV base case (computed using an energy balance), savings simply due to occupant behavior (and related tolerance of a wider range of interior comfort conditions) may play an important role in the values reported by Ezzeldin [46].

Table 4 Comparative results of natural ventilation studies reviewed

Author	Location	Type	Actions	Salient Results
Taleb [31]	Dubai	Villa	A wind catcher and cross ventilation is modeled in conjunction to 6 further passive cooling strategies	Reduction of 23.6% of all measures combined (no individual result due to ventilation strategies given)
Al-Sallal et al. [25]	Abu Dhabi	Villa	Two wind towers and a courtyard were included in a design study of a sustainable house as part of a number of additional passive cooling measures	Collective effect of all measures is a 59% reduction in GHG emissions and utility bill; individual performance of ventilation strategies is not presented
Taleb [43]	Dubai	Villa	Impact of 5 cross ventilation timing schedules (daily and seasonal) on energy and interior temperature	30% savings in total energy by using natural ventilation instead of AC during the winter months
Aboulnaga et al. [44,45]	Al Ain	Two story residential	Investigation of the attainable flow rates for a different solar chimney configurations	Flow rates obtained (up to 26 air changes per hour) sufficient to provide required cooling for a residential building

Ezzeldin et al. [46]	Manama (Bahrain)[1]	Office high rise	A number of mixed mode ventilation combinations were explored	Using mixed mode ventilation over base case VAV yields plant energy savings of up to 63% Augmenting mixed mode ventilation with night ventilation yields savings of up to 79% over base case VAV

The above results indicate that natural ventilation is an effective passive cooling strategy that should receive more attention to reduce the environmental footprint of the UAE built environment. The strategies are based in or evolved from pre-air conditioned times, however have been neglected due to the cheap availability of electricity and cooling by mechanical means.

8. Further occupant-based measures

Occupant behavior and interior set points play a critical role in energy conservation [47], and while they do not constitute a part of the building envelope, a number of the studies reported in this review include energy savings results based on a change of internal set point. The magnitude of the reported energy savings based on increasing the set point provides a sharp contrast to the expense and effort required to achieve similar savings using constructive measures [2].

Friess et al. [12] report that changing the interior set point of a typical UAE villa from 22°C in the living areas and 21°C in the bedrooms to 25°C and 24°C respectively generates on the order of 40% energy savings over the poorly insulated as-built case, reducing to 14.3% for a fully insulated perimeter.

Radhi [13], and in the context of UAE residential buildings, reports the possibility of similar savings (between 26.8% and 33.6%).

Afshari et al. [5] examines a number of retrofits (including adjusting the internal set point) of a fifteen story mixed-use office building built prior to any energetic standards being implemented in Abu Dhabi. The cooling set point in the base case is 22°C. The authors report that by increasing the set point to 23°C, 24°C, 25°C and 26°C, the annual cooling load reduces by 8%, 16%, 23% and 29% respectively.

AlFaris et al. [48] examined the effect of a range of envelope and systems retrofit measures on 10 villas in Abu Dhabi, reporting that the combined effect (no detailed listing of individual savings is provided) ranges from 14.4% to 47.6% in electricity savings. The authors report that the difference in the individual energy performance of the villas was a caused by differing levels of occupant understanding and associated energy saving behavior.

The astounding numbers reported in these studies underscore the importance of occupant behavior and popular awareness of environmental considerations in the overall scope of energy savings in the UAE.

9. Conclusion

The studies reviewed here confirm that building envelope measures have the potential to significantly reduce the energetic footprint of the UAE built environment, which over the past four decades has been shaped by the lack of energetic codes combined with the need for rapid construction due to the frantic growth of the country.

[1] While this building is not located in the UAE, the climatic conditions in Bahrain are very similar, and thus these results offer insights into possible strategies applicable to the UAE.

These measures can be developed at different scales; while large scale urban planning has been shown to be able to improve dwelling cooling and ventilation between 8% and 30%, more modest small-scale envelope optimization, in particular orientation and surface area of windows, can reduce up to 55% of the cooling load in a residential building. Further architectural solutions, such as the culturally and historically rooted addition of a central courtyard, has also shown promising effects on reducing solar heat gain and improving natural ventilation in low rise residential buildings, with reported energy savings between 6.9% and 8% over different base cases.

Heat transmission through opaque building enclosures has been shown to be a significant energy loss mechanism, in particular in residential buildings as they exhibit lower window-to-wall ratios than the glass dominated office high-rises. Adding insulation to otherwise un-insulated walls is highly effective; all reviewed studies indicate improvements upon adding insulation or increasing the thickness of the insulation, albeit with diminishing returns as the insulation thickness increases. Thermal bridges are a common occurrence, in particular in buildings built under early regulations prescribing at least some insulation, and studies show that addressing these can significantly reduce building energy consumption.

In order to reduce the heating of external surfaces (which in turn increases heat conduction through the walls), two primary strategies have been reported: the use of external cladding systems that reduce the solar absorption (reduction of up to 1.9% in the building cooling load), as well as the use of vegetation both as shade generators detached from the building, and for greening the roof and walls.

Windows and glazing constitute a critical link in achieving better energetic efficiency in building enclosures in the very high solar irradiance UAE climate. Addressing solar heating through windows becomes more important in mixed-use and office high-rise buildings, which often follow the global trend of being fully glazed, than in the residential environment, where glazing only occupies a small fraction of the building enclosure. The reviewed work indicates that while changes in glazing from single pane to double pane solar control can have a significant effect (over 12% in the case of a mid-rise residential building), further improvements in glazing again show diminishing returns. However, external shading in the form of louvers and/or vegetation has shown to be highly effective (28% to 34% in cooling energy). In addition, these shading strategies also improve excessive lighting levels and solar glare. Proper window orientation has been shown to decrease energy consumption by up to 55%.

Natural ventilation represents a challenge in the hot climate of the UAE, and has not received much attention since the advent of cheap electricity and air conditioning has allowed direct control of indoor comfort levels. However, the current renewed attention to energy conservation is generating a number of exploratory studies on this subject, with encouraging results. In particular, in low-rise residential buildings the use of natural ventilation strategies during the times when the outdoor climatic conditions allow for natural cooling (simply by opening the windows instead of operating the air conditioning) has been computationally examined, with reported savings up to 30% of the cooling energy. In addition, components of the traditional Middle Eastern architecture such as the wind tower and the courtyard, in combination with solar chimneys, are being reintroduced and analyzed for feasibility under modern indoor comfort level requirements. The studies also extend to quantitative assessment of using mixed mode ventilation in high-rise buildings in similar climates, again reporting energy savings from 35% to 73% depending on the strategy employed.

The above conclusions indicate that very significant energy savings can be attained in the UAE by addressing the building envelope and implementing low energy ventilation strategies. However, in order to effectively enact these savings, it is not sufficient to implement stricter regulations for new construction, but also to develop retrofit measures that can be applied to the extensive existing building stock. In addition to these measures, increasing the public awareness of the effect of occupant behavior on the utility bill, which in the studies reviewed here has been reported to decrease energy consumption between 8% and 40% depending on the specific building characteristics, should provide a strong contribution toward mitigating the excessive energy consumption and environmental footprint of the UAE.

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