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A review of the energy implications of passive building design and active measures under climate change in the Middle East

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Abstract

As buildings consume fossil fuel-based energy, they contribute to greenhouse gas emissions which raise global temperatures. Buildings will then require more energy for cooling to guarantee indoor thermal comfort, thus creating a positive loop between cause and effect. In the Middle East, this is particularly harmful to the environment because it increases the cooling demand in countries with an energy grid based on fossil fuel. By reviewing the latest scientific contributions, this paper analyzes different passive and active design measures, gathers mitigation and adaptation strategies, and identifies the main barriers. Due to an economy based on an energy mix of low-tariff fossil fuel, Middle East countries lag in adopting clean energy systems and energy-efficient solutions. In conclusion, there is great potential in using passive design, efficient air conditioning systems, and integrating renewable energy in buildings.

Keywords: climate change, built-environment, hot-climate, cooling passive measures, photovoltaic systems, Middle East

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Highlights

- Studies assessing passive design in the Middle East under future conditions are few
- The implementation of passive measures may reduce building cooling demand
- District cooling systems may lead to a reduction in building energy demand
- Investment in renewable energy will diversify energy sources

1. Introduction

The climate change phenomenon is the observed change in the composition of the global atmosphere over comparable periods attributed directly or indirectly to human activity in addition to natural causes (United Nations, 1992). The dominant cause of the observed warming results from anthropogenic drivers. Indeed, the increase of greenhouse gases (GHG) is responsible for more than half of the observed rise in global average surface temperature between 1951 and 2010 (*Climate Change 2014: Synthesis. Report Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 2014). Energy services in and related to buildings account for approximately a third of the total global final energy demand (Urge-Vorsatz et al., 2013) and associated CO_2 emission. Moreover, growing urbanization affects the ecosystems of an urban area and changes in the land surface's biophysical properties, which is the main cause of the Urban Heat Island (UHI) effect. UHI affects the overall building energy demand in urban or suburban areas, but the effect varies depending on the climate region (Boccalatte et al., 2020; Xu et al., 2018).

The built environment and climate change have three interrelated effects. The first effect occurs during the built environment's operational phase when GHGs are emitted, contributing to global warming. As the temperatures rise in the outdoor environment, buildings will consume more energy for cooling to regulate their indoor environment (Andrić et al., 2019). In the second, the UHI is enhanced by global warming (McCarthy et al., 2010), leading to higher energy consumption and, ultimately, increasing GHG emissions. The last effect occurs when urban microclimates influence the local building energy demand. This effect happens due to the local urban morphology and used materials (Mauree et al., 2019). These relations are depicted in Figure 1.

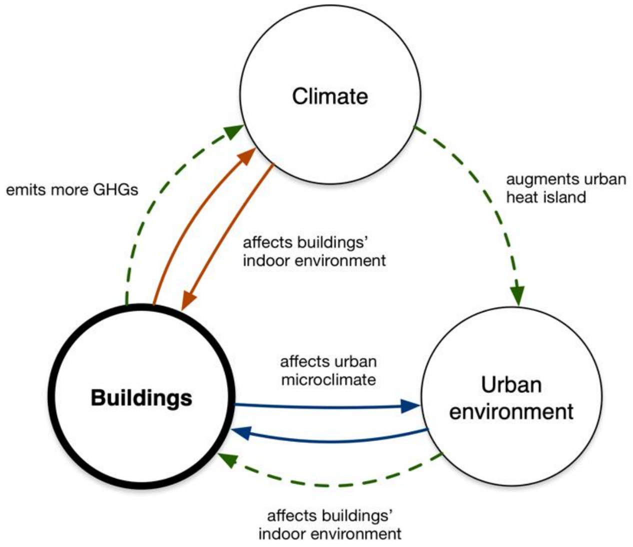

Figure 1: Interrelation between climate, urban environment, and buildings on building performance.

Buildings and urban microclimates are responsible for a significant proportion of energy consumed and CO_2 emissions, and buildings' heating and cooling needs are among the few areas in which a several-fold reduction in emissions and energy use is possible (Ürge-Vorsatz et al., 2020). The building stock can considerably reduce energy demand by using different strategies (Hrabovszky-Horváth et al., 2013). In a wide variety of climates, geographies, and cultures, buildings' climate neutrality might be achieved by improving the building materials and design (Ferreira et al., 2016).

In the future, climate change will severely affect hot and arid climate regions, particularly the Middle East and North African countries. These countries are characterized by their higher cooling energy demand (Alalouch et al., 2019), and, therefore, global warming will increase such demand.

A summary of studies investigating the impact of climate change on building energy use in this region is presented in Table 1. According to these studies, climate change significantly impacts the built environment and air-conditioning energy use in these countries. For example, in the cases of the UAE (Radhi, 2009) and Iran (Roshan et al., 2012), the statistical analyses of the effects of climate change on degree-days under different climate change scenarios resulted in the positive impact of climate change on the heating degree and the negative influence on cooling-degree days and consequently cooling demand. In Turkey, climate change will increase the cooling load in air-conditioned buildings (Dino and Meral Akgül, 2019). Moreover, under a mix-mode and fully air-conditioned cooling scenario, the growth rate is different. Comparing energy consumption between the present and future climate conditions demonstrates an energy demand rise in Qatar due to more frequent and longer heatwaves with greater intensity (Andric and Al-Ghamdi, 2020). Higher consumption could lead to a 5.4 % increase in CO_2 emission over the next few decades in the UAE (Radhi, 2009) and an additional 17.5 t CO_2 eq per household in Qatar on an annual basis (Andric and Al-Ghamdi, 2020).

Table 1: Studies using future climate to analyze building energy demand in the Middle East.

				Impact on the building energy demand		
Study	**Country**	**City**	**Target year**	**Cooling demand**	**Heating demand**	**Total energy demand**
Radhi, 2009	United Arab Emirates	Al-Ain	2050	+7.3 % to +24.1 %	-9.5 % to -39.2 %	+4.1 % to +12.5 %
Roshan et al., 2012	Iran		2050	+30 %	-14%	
Roshan et al., 2019	Iran	Bushehr	2060	+14.3 %		
		Bandarabbas		+14.2 %		
		Chabahar		+13 %		
Dino and Meral Akgül, 2019	Turkey	Izmir	2060			up to +41 %
		Istanbul				up to +37 %
		Ankara				up to +4.2 %
		Erzurum				-2.4 %

Andric and Al-Ghamdi, 2020	Qatar	2080		+30 %

As global warming increases cooling demand, the nefarious effects on human health and productivity must be prevented by better understanding the relations between climate change and the built environment (Mcmichael et al., 2006). Deaths, hunger, and illnesses are associated with changes in the overall ecological system due to the spread of infectious diseases and shortages in food and water (Confalonieri, U., B. Menne, R. Akhtar, K.L. Ebi, M. Hauengue, R.S. Kovats, 2007). Therefore, this study reviews scientific publications on adaptation and mitigation measures, particularly passive design and active strategies on a building and urban scale in the Middle East.

2. Methodology

In order to collect, analyze, and synthesize findings on the impacts of climate change on the energy performance of the built environment in Middle Eastern countries (in particular, Bahrain, Egypt, Iran, Iraq, Kuwait, Oman, Qatar, Kingdom of Saudi Arabia – KSA, Turkey, and United Arab Emirates – UAE), a methodology consisting of three phases was used. Figure 2 depicts the locations analyzed in the reviewed studies – the majority of these countries have a hot desert or arid climate (Table 2). The study concept framework is depicted in Figure 3.

In the first phase (literature survey), three steps were carried out: (i) a preliminary survey was done in two search engines, Scopus and Google Scholar, using search keywords “buildings,” “energy,” “hot climate,” or “Middle East,” and “climate change”; (ii) classification criteria were determined for four categories, specifically urban design, building passive design, active systems, and energy-efficient systems; and lastly (iii) a deeper and detailed literature survey was carried out within each category using specific keywords (Figure 4). A publication interval was applied to each category (from Jan 1st, 2008 to Dec 31st, 2020) to focus on the latest scientific contributions. After eliminating duplicates, 148 documents were retrieved divided into the following categories: 20 in the urban design, 63 passive design, 15 active design, and 50 energy-efficient systems and others.

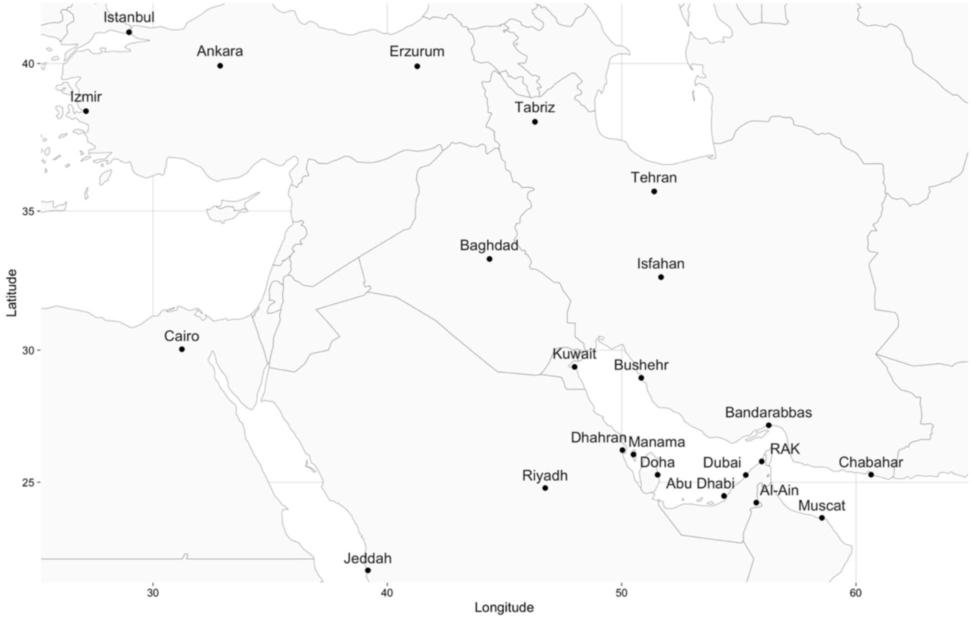

Figure 2: The map of the Middle East region with the locations described in the studies.

Table 2: Climate classification and description in the Middle East (Kottek et al., 2006).

Country	City	Climate Classification	Description
Qatar	Doha	BWh	Desert or arid climates have an excess of evaporation over precipitation. In summer, scorching, desiccating heat prevails.
Bahrain	Manama		
Egypt	Cairo		
Iraq	Baghdad		
Kuwait	Kuwait		
Oman	Muscat		
KSA	Riyadh Dhahran Jeddah		
UAE	Dubai		

	Abu Dhabi		
	RAK		
	Al-Ain		
Iran	Bushehr		
	Bandarabbas		
	Chabahar		
	Tehran	BSk	Cold semi-arid climates normally have warm to hot-dry summers; however, summers are not as hot as hot semi-arid climates. These climates have cold winters.
	Isfahan		
	Tabriz		
Turkey	Izmir	Csa	Mediterranean hot summer climates usually have hot summers and mild, wet winters.
	Istanbul		
	Ankara	Dsb	Mediterranean-influenced warm-summer humid continental climate.
	Erzurum	Dfb	Warm-summer humid continental climate.

In a second phase (data curation and tabulation), documents were first categorized into two scales: urban and building. The urban section included the most efficient urban design strategies while the building scale encompasses two main envelope-related categories: a) passive design measures and b) active measures – since the region has high solar radiation, the assessment was limited to solar systems in buildings. Also, the impact of efficient systems being used in the buildings was analyzed and discussed. The selected documents were then analyzed to extract data on the country, relevance, objectives (energy saving percentages), results, and conclusions. The information was tabulated for passive and active categories (Tables S1 and S2 in Supplementary Material).

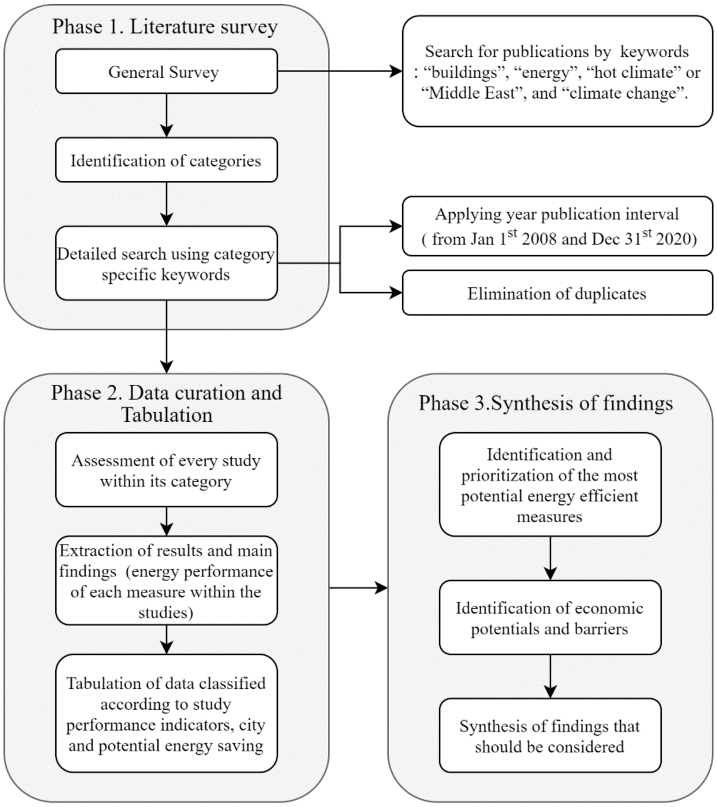

Figure 3: Study concept framework.

In the last phase (synthesis of findings), the tabulated information was used to identify and prioritize the most promising energy-efficient measures for the built environment in the context of the Middle East. The economic viability of some of the measures was also analyzed to understand their sustainability. The cost-saving potential and economic barriers of the measures were presented. This research does not cover non-scientific publications, including building programs, building codes, and national policies. Thus, their perspective is not considered in the selected literature.

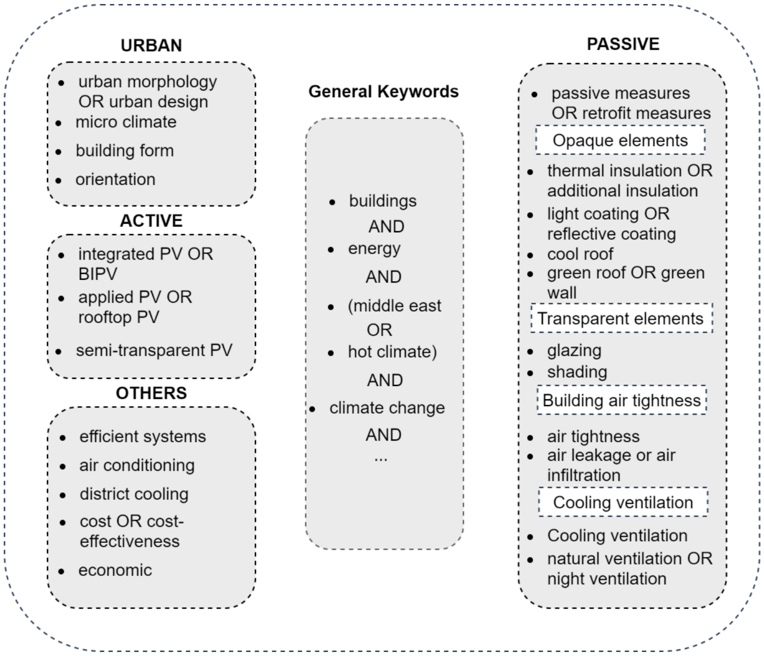

Figure 4: Representation of general and specific keywords used for each category.

3. Design strategies at an urban scale

The expansion of cities due to rapid urbanization has influenced their morphology and density (Xu et al., 2019), leading to an increase in energy consumption. Urban climate and climate change exacerbate energy needs (Nik, 2012), but with urban planning aid, there is a high potential for mitigating climate change using strategic tools (Newman, 2020).

A UHI is defined as the temperature difference between the urban area and the surrounding rural area generated from urban structures and anthropogenic heat sources (Rizwan et al., 2008). This temperature difference increases buildings' energy consumption in urban areas compared to rural areas (Javanroodi et al., 2018). The urban morphology thus influences cooling energy demand, particularly in the parameters of density, compactness, building form, the geometry of canopies, building height to street width ratio (H/W), among other factors (Javanroodi et al., 2018).

The needs of residential and commercial buildings in countries with hot-arid climates are mainly characterized by their cooling demand (Gou et al., 2018). Studies demonstrate that higher urban density or compactness lowers cooling loads (Javanroodi et al., 2018) and CO_2 emissions of buildings in a neighborhood located in a hot-arid climate (Fahmy and Sharples, 2011). By increasing the urban density, the energy performance was improved as the higher density blocked solar rays, providing more shade (Mirkovic and Alawadi, 2017). Comparatively, compact horizontal housing configurations result in higher energy savings than vertical configurations in hot climates (Asfour and Alshawaf, 2015).

A denser neighborhood with building height-to-street width (H/W) ratios of 12 for newly-built buildings was recommended in Tehran (Javanroodi et al., 2018). A deep street canyon produces higher energy performance by reducing solar radiation and heat gain from outside the canyon in the city of Al-Ain (Hamdan and de Oliveira, 2019) and in Egypt (Abdallah, 2015). Also, in Egypt, reflective pavements in streets with a higher H/W ratio reduced the air temperature in shaded street canyons (Fahmy et al., 2017). When considering natural ventilation, the best performance was obtained through urban streets and canopies with a H/W ratio ranging between 6 and 8 (Javanroodi et al., 2018). Therefore, the building-street proportion has a dual impact on the cooling demand. While a higher H/W ratio decreases solar exposure and reduces cooling demand due to shading from the buildings (Shishegar, 2013), a lower H/W ratio contributes to a higher cooling energy reduction when associated with a natural ventilation strategy. Nevertheless, in a hot arid climate, shading had a higher impact than wind (Hamdan and de Oliveira, 2019).

In future climate scenarios, these temperature reductions will be smaller and cannot guarantee thermal comfort in buildings (Fahmy et al., 2017). Nonetheless, if 70 % of the outdoor area in neighborhoods with a H/W ratio of 1/1 is paved with grass, reductions are still possible both in air temperature and energy demand (Aboelata, 2020). Among other different green structures, trees effectively reduce energy use in very high-density built-up areas due to humidity and evaporation (Aboelata and Sodoudi, 2020). They are, however, ineffective in low-density built-up areas.

Relatively to the design configuration of open urban spaces, in Egypt, linear type spaces with a 1/3 aspect ratio and a space proportion of 1/2 between width and length have the strongest influence on reducing total solar radiation on the façades of surrounding buildings (Bahgat et al., 2020). For both linear and clustered types, the East-West orientation of open spaces obtained the highest rate of total solar radiation reductions (Bahgat et al., 2020).

As for building orientation, according to the studies on the hot climate of KSA (Khan and Asif, 2017), Iran (Fallahtafti and Mahdavinejad, 2015), and Egypt (Asfour and Alshawaf, 2015), the most suitable orientation for reducing energy consumption is having shortest façades oriented east and west. This orientation has the largest façade facing south to receive maximum solar radiation in winter but, during summer, shading devices must be used to reduce solar gains. Energy savings can also be improved by having smaller glazing areas in the west façade (particularly in high-rise buildings) (Javanroodi et al., 2019).

It is known that a high surface-area-to-volume ratio in urban building forms can lead to higher heat gain in warmer climates (Ratti et al., 2003). Consequently, to achieve the optimal form in such climates, the external surfaces should be minimized (Aksoy and Inalli, 2006). In Baghdad, the square-shaped building could achieve an approximate 30 % savings in energy compared to the other forms. Buildings with lesser surface area to the same volume have higher energy conservation (Hasan, 2018). Nonetheless, L-shaped buildings have revealed a higher potential for reducing cooling loads in Tehran (Javanroodi et al., 2018), even though this is not the optimal form.

Window area or a window-to-wall ratio (WWR) is an important factor affecting a building's energy performance. By decreasing the area of glazing, solar heat gain is reduced; therefore, the amount of cooling demand required to reach indoor thermal comfort decreases (Andrić et al., 2019). In contrast, other studies found an increase in heating demand upon the increase of glazing area. In the UAE, the impact of the window surface area depends on the climate scenario (Radhi, 2009). In Oman, a 10 % increase in WWR led to a 4 % change in energy consumption (Al-Saadi and Al-Jabri, 2017). In Egypt, annual energy savings of 24 % could be reached with a 20 % WWR and openings with a 1/2 height-to-width ratio facing north (Elghamry and Hassan, 2020).

However, in a commercial building in the same region, altering the WWR from 40 % to 20 % reduced cooling load between 2 % to 12 % (Samaan et al., 2018). In another commercial case, in Turkey and Italy, a smaller WWR led to a 20 % reduction in cooling demand (Schulze and Eicker, 2013). As expected, the highest savings in cooling demand are related to the smallest relative window sizes (Prieto et al., 2018). A larger windows area is more beneficial in a hot-humid climate than in a hot-arid one (Alwetaishi, 2019). Glazing areas should also be minimized in south and east façades since they are more exposed to solar radiation (Alwetaishi, 2019). When comparing the impact of glazing in warm-dry and warm-humid climates, higher cooling energy savings are obtained in warm-dry climates (Prieto et al., 2018).

4. Design strategies on a building scale

In hot-arid climates, the main objective is to decrease heat gain, particularly through the building envelope. Design strategies on a building scale may be classified into two main categories: passive strategies and active measures.

4.1. Passive strategies

Passive design refers to systems or structures that use natural resources directly to achieve the goal without using electricity or fuel (Spacey, 2017). Passive measures reviewed in this section include adding insulation to opaque elements, reducing thermal transmittance, reducing solar heat gains in glazed surfaces, improving airtightness, using cooling ventilation, implementing evaporative cooling, adding shading to glazed areas, and using green façades and roofs. Table S1 presented in Supplementary Material summarizes the findings of the reviewed documents.

4.1.1. Opaque elements

Heat exchange between the indoor and the outdoor environment is limited by adding insulation to the opaque elements, thus preserving thermal comfort for longer periods (Konstantinou and Prieto, 2018). Therefore, it is essential to find the right amount of thermal resistance for the buildings' envelope, especially in warm climates, to balances heating and cooling energy consumption (Fernandes et al., 2019). A recent study has demonstrated that today's ideal thermal transmittance values (*U*-value) may prevent overheating in future climate change scenarios (Rodrigues and Fernandes, 2020). For example, in Al-Ain, heating and cooling demand may be reduced up to 23.8 % and 19.7 %, respectively, when using a low *U*-value envelope in a residential building (Radhi, 2009), thus decreasing total energy consumption by up to 15.9 %. When insulation is added to the roof and external walls, the decrease in energy consumption amounts to 12.1 % and 3.9 % in Oman, respectively (Al-Saadi et al., 2017). However, another study on residential buildings in Omani revealed that increasing thermal insulation beyond 15 cm in both walls and roof does not significantly impact energy-savings (Al-Saadi and Al-Jabri, 2017).

Reducing the wall *U*-value in commercial buildings from 1.71 $W/m^2 \cdot K$ to 0.324 $W/m^2 \cdot K$ only reduced 2.6 % of the annual cooling load in the UAE (Afshari et al., 2014). This low percentage is due to the higher ratio of window-to-wall in commercial buildings (70 % WWR in the reviewed case) than in residential ones. Similarly, adding 5 cm of expanded polystyrene to external walls had no effect on average energy consumption in three educational buildings in Egypt (El-Darwish and Gomaa, 2017). As mentioned above, these results are due to the envelope of commercial buildings being mostly covered in glazing.

Reduction of heat flux through materials with a higher thermal resistance (*R*-value) and solar reflectivity can also reduce cooling load. An experimental study in UAE demonstrated that replacing solid concrete with polyisocyanurate and reflective coatings or applying exterior insulation finishing systems obtained 25.3 % energy-savings (Rehman, 2017).

Thermal mass – the property of a building to store heat during the day and release it during the night (Reilly and Kinnane, 2017) – is used in construction to attenuate the fluctuations of indoor temperature (Ascione, 2017). This phenomenon may play an important role in regulating the indoor environment. Nonetheless, to fully benefit in an energy assessment over a whole year from thermal mass, the buildings' envelope would require adequate *U*-values (Rodrigues et al., 2019). In future climate conditions, a high thermal mass was found to reduce heating energy between 21.5 % to 27.2 % in a residential building in the UAE (Radhi, 2009).

Light coating colors and reflective coating can reduce the building's temperature and decrease cooling demand (Taleb, 2014). In a study on walls with different coatings and reflective rates, the higher reflectivity rate presented the largest energy-saving due to reduced heat transfer from the exterior to the interior wall (Taleb, 2014). In a house in Qatar, a 12 % reduction in cooling load may be obtained by changing the color of the external shell from medium to light colors (Kharseh and Al-Khawaja, 2016).

In an energy assessment over a complete year in Iraq, the application of high-reflective roofs (both solar reflectance and thermal emittance of 0.8) was found to save up to 73 % in houses (Mohamed et al., 2015). The same study suggests using cooling roof solutions on a large scale, thus changing the albedo in Iraqi cities. In the same region, energy simulation on three different roofing technologies (external roof coatings, internal coatings, and radiant barriers) reduced the cooling load by approximately 20 % compared to typical roofs in Iraqi houses. Although internal coating and radiant barriers played a role in reducing energy loads, they were not as effective as the solar reflectance of external coatings (Mohamed et al., 2016).

In Egypt, vaulted roofs with high albedo coating are predicted to perform more efficiently when considering reductions in cooling demands. In this study, several roof designs were modeled by altering roof shape (flat roof, double roof, dome, vault, and ventilated) and roof material (insulation, albedo, an air gap, and water). From the studied cases, the vaulted roof with a rim angle of 70° and a high albedo coating reduced cooling demand by 53 % and shift heat gain from day to night (Dabaieh et al., 2015). Another comparative study in Egypt confirmed that applying reflective painting on the outdoor roof surface obtained higher cooling demand reductions than applying green or sloped roofs. This strategy also performs more efficiently in hot arid climates than in hot humid or moderate humid climates (Mahmoud and Ismaeel, 2019).

In KSA, a cool roof increases the heating load and decreases cooling loads. However, the cooling load reduction is typically much greater than the heating load increase, resulting in a higher energy-saving (Algarni, 2019; Saber et al., 2019). Additionally, it was revealed that less roof insulation could be considered in building code regulations if a reflective roof is installed (Saber et al., 2019). Replacing a typical or dirty roof with a cool roof (solar reflectance of 0.85 and infrared emittance of 0.9) could lead to a peak conduction decrease by up to 71 % and 51 %

compared to the dirty or typical roof, respectively. Nevertheless, being exposed to the common dust storms and, consequently, accumulating dust and dirt on a building's roof make cool roofs' efficiency lower and their maintenance more difficult in this region (Algarni, 2019).

Green roofs and façades are other strategies to lower energy loads by adding vegetation to produce evaporative cooling on the outer surface of the building components (Ascione, 2017). In addition, these improve the exterior and interior air quality, increase energy efficiency, protect the building structure, and reduce noise (Sheweka and Mohamed, 2012). These are also known to reduce the effect of UHI. In Iran, a green roof was the most efficient action in reducing energy loss in the whole building envelope by 42.9 % (Goudarzi and Mostafaeipour, 2017). Understandably, the benefits of green roofs are inversely proportional to the number of building floors. In the mixed dry climate of Tabriz in Iran, the relative cooling energy saving in buildings with fewer floors (single story) is much higher (46.3 %) than in three-story buildings (22.9 %) (Refahi and Talkhabi, 2015). In Al-Ain (UAE), a green wall contributed to 20.5 % energy savings due to the plants' low thermal conductivity, the soil's high thermal mass, evaporative cooling from irrigation, and shading from the vegetation leaves (Haggag et al., 2014).

Comparing full-intensive, semi-intensive, full-extensive, and semi-extensive roof types under hot-dry, hot-humid, warm-humid and temperate climates in three urban densities, the hot-arid climate of Cairo with a full-intensive green roof and low urban density revealed the highest electricity peak reduction (5.2 %). In contrast, green roofs were the least effective in temperate climates, demonstrating the importance of relative humidity and solar intensity in their efficiency (Morakinyo et al., 2017).

Similarly, in KSA, a green roof strategy reduced energy demand in Riyadh's hot and dry climate by 6.8 % and by 6.7 % in the hot-humid climate of Dhahran (Khan and Asif, 2017). In a recent study, the application of green roofs and walls resulted in only 3 % energy savings in a residential villa in Qatar, in which simulations were carried out under weather scenarios created for the years 2020, 2050, and 2080. However, the authors emphasized other positive aspects of green roofs and walls, such as the impacts on air quality, heat island effect, and inhabitants' health, together with the environmental impact of green infrastructure (Andric et al., 2020). Nevertheless, vegetation increases maintenance costs and water consumption due to irrigation, and the lack of water is crucial in hot-arid climates.

4.1.2. Transparent elements

The poor thermal properties of windows may be improved by multiple glass panes, separated by air gaps, instead of single-glazed window panes (Konstantinou and Prieto, 2018). Windows may be further enhanced by reducing the gap's conductance by filling it with slow-moving gas such as argon and krypton (Konstantinou and Prieto, 2018). Low-emissivity coatings can also be applied to decrease the surface emissivity of glass. For example, in hot climates, a coating is installed on the outside face to reflect the solar radiation to the environment (Konstantinou and Prieto, 2018). Excess solar radiation may be avoided with sensitive glazing, which changes transparency, according to outside solar intensity (photochromic), temperature (thermochromic), or when activated by an electric charge (electrochromic) (Ascione, 2017).

In the case of a residential building in the UAE, adequate use of window parameters reduces both cooling and heating energy consumption. Replacing single glazing with double glazing provides a 10.5 % saving in cooling energy demand and between 8.7 % to 10.9 % saving in heating energy demand under different scenarios (Radhi, 2009).

Based on different studies, the reduction of cooling demand associated with efficient glazing measures varies between 2 % to 49 %—such a large difference in cooling energy savings results from the combined use of different measures. Merely replacing a single layer with a double window layer would not significantly increase energy savings. Namely, in a residential building in Oman, double glazing, as opposed to single glazing, only contributed to a 4.5 % reduction in cooling load (Kharseh and Al-Khawaja, 2016). In the same situation, altering two parameters in the glazing properties, replacing the single glazed window-aluminum frame with a double glazed window, filled with low emissivity gas, resulted in higher energy savings of 8 % (El-Darwish and Gomaa, 2017). The annual heating and cooling demand could be reduced by 9 % to 10 %, respectively, and nearly 3 % in Iran by replacing double glazing windows with triple glazing filled with air, argon, and krypton (Hosseini et al., 2020).

When filling double-pane-tinted low emissivity glazing with argon – characterized by low solar heat gain coefficient and low *U*-value – HVAC load reduced 25 % in KSA (Dehwah and Asif, 2017). The application of different dynamic glazing, such as reflective, aerogel, electrochromic, tinted-glazing, gasochromic, and thermochromic, resulted in a 49 % reduction in the air conditioning load in commercial buildings in Dubai (Bahaj et al., 2008) and (up to 46 %) in Egypt (Nageib et al., 2020). The latter also reduced consumption of lighting energy up to 61 %. Nevertheless, due to their high cost, the use of such systems is still limited (Prieto et al., 2018). It should be remarked that the application of new types of glazing to reduce cooling load does not always result in the reduction of lighting energy and provide a visually comfortable space. A study on commercial buildings in the UAE proved that although tinted glazing with 40 % coverage can decrease cooling demand by 23 % when addressing lighting demands for offices

(300 lx to 500 lx), single glazing had better performance. Higher lux and lower *U*-value are possible by filling windows with gases such as krypton and xenon (Taleb and Antony, 2020).

A recent study revealed that using solar window film on the interior of a double-glazing window in an office building in Kuwait can increase indoor humidity, decrease air temperature, and reduce light intensity and, therefore, having higher energy savings (Sedaghat et al., 2021).

4.1.3. Building airtightness

In addition to the characteristics and construction flaws in the building envelope, temperature differences and wind are the major environmental factors that affect the air leakage flow (Al-Saadi and Al-Jabri, 2017). Therefore, by controlling these infiltrations with sealants, gaskets, or additional window panels, the energy performance may be improved (El-Darwish and Gomaa, 2017). For example, reducing the air changes per hour (ACH) to 0.5 and 0.3 led to 4.8 % and 9 % energy savings in residential buildings in Oman's humid climate, respectively (Al-Badi and Al-Saadi, 2020; Al-Saadi and Al-Jabri, 2017). Similarly, airtightness retrofit showed a reduction of up to 5.6 % in a building in the UAE (Afshari et al., 2014).

However, applying sealing around windows, vents, and doors had little effect on energy reduction (about 2 % on average) in an educational building in Egypt (El-Darwish and Gomaa, 2017). Due to the nature of their operation and functions (uncontrolled door operation during occupancy), in these types of buildings (educational buildings or mosques), different levels of air infiltration rates and lower efficiency should be assumed for the simulation (Budaiwi and Al-homoud, 2013). Notwithstanding, the proper door design may reduce uncontrolled air penetration (Budaiwi and Al-homoud, 2013).

Nonetheless, reducing air infiltration to lower than 0.5 ACH lowers the indoor air quality and, therefore, making a balance between saving energy and keeping the high quality of indoor air another important aspect worth considering (Al-Badi and Al-Saadi, 2020).

4.1.4. Ventilation strategies

Adequate ventilation strategies may improve the building's energy performance without comprising indoor thermal comfort (Fernandes et al., 2020). However, the overall impact of natural ventilation varies widely in hot-arid climates. For example, over-ventilating may lead to undesired heat gains from the outside and exfiltration of cool indoor air. In Egypt, hybrid ventilation can reduce energy consumption between 56 % to 79 % under different scenarios (Ezzeldin and Rees, 2013). The low diurnal ventilation rate in summer and night ventilation strategies reduced cooling loads up to 19 % (Samaan et al., 2018). In Iran, combined strategies have higher benefits from fresh air, such as using a windcatcher to reduce cooling energy by 68 % in a residential house (Goudarzi and Mostafaeipour, 2017).

Alternatively, integrating cavity ventilation in double-skin façades with external louver shading reduced energy by14.8 % in hot-dry climates (Zomorodian and Tahsildoost, 2018). Also, the combination of natural passive ventilation and active cooling systems (HVAC) can reduce cooling load and cooling energy consumption. In the UAE, this combination under different scenarios could reduce cooling demand by approximately 30 % compared to HVAC systems working throughout the day all winter long (Taleb, 2015).

Additionally, building thermal mass is an important parameter that has been considered in several studies focusing on natural ventilation strategies (Ezzeldin and Rees, 2013). Thermal mass is also known to play an important role in the overall performance of purge night ventilation. Materials with dynamic thermophysical properties, such as phase-change materials, were found to achieve a 46.5 % reduction in the cooling load of an office building in the hot-arid climate of Yazd (Solgi et al., 2016).

Evaporative cooling is another effective passive cooling technique that has been applied in many countries in the Middle East, particularly in those with a historically hot-arid climate, such as

Iran and Egypt (Saadatian et al., 2012). In this measure, the absorption of surrounding heat by water and the consequent vaporization of water leads to a reduction in outdoor air temperature (Hughes et al., 2012), contributing to reducing air temperature inside the building (Kamal, 2012). Nonetheless, some traditional ways of evaporative cooling use, such as a Qanat (underground water canal) and water pond, are not readily applicable in present buildings (Saadatian et al., 2012). The integration of an evaporative cooling technique with other passive or active measures has been considered in different studies. For example, in the UAE, two fountains were placed near a building, with other passive measures, to produce a 9 % reduction in cooling load (Taleb, 2014).

The application of a new system applied to windows in typical office spaces, composed of a solar chimney above the window, a glazing section, and an evaporative cooler (water-absorbing sheets) below the window, contributed to an 8.8 % reduction in total annual energy demand in Doha. This solution uses potential solar energy resources to decrease the window surface temperature and corresponding indoor energy demands. The results showed a performance improvement of the system in summer days, while during the winter, the efficiency reduced due to higher humidity (Al Touma and Ouahrani, 2018). It is noteworthy that the evaporative cooling system performs more efficiently in climates with high temperatures and low humidity.

In a study of a building in Iraq, the efficiency of the air conditioning system was improved by integrating a supportive evaporative cooling system with a window-type air conditioning system (Eidan et al., 2017). The solution indicated that the aid of the evaporative cooling system contributes to a significant improvement in the coefficient of performance, cooling capacity, and energy savings by precooling the air before flowing through the condenser.

4.1.5. Shading devices

Shading devices in buildings can be fixed, movable, or other types. Each may be classified into vertical (placed in parallel to the glass plane or perpendicular on the sides of the window) or horizontal systems (overhanging shadings) (Bellia et al., 2014). Despite being used to reduce insolation, these devices can also reduce the amount of daylight received in spaces and impact the electric energy consumed in the building. Nonetheless, this issue can be minimized by using solid-state lighting, such as light-emitting diode technology.

Relatively to reducing solar gains, savings in electricity consumption in residential buildings were 2.9 % in the UAE (Radhi, 2009) and 2.3 % in Oman (Al-saadi and Al-jabri, 2020; Al-Saadi and Al-Jabri, 2017). Nonetheless, shading strategies can work alongside other envelope passive strategies or in different types of buildings. In the case of a residential building, the maximum percentage of energy-saving was approximately 9.4 % (Al-Badi and Al-Saadi, 2020). However, in mosques, due to the small area of windows, this strategy had a lower impact (less than 1 %) on energy savings (Budaiwi and Al-homoud, 2013). While the use of shading devices in commercial buildings showed to have a higher percentage of energy savings, varying from 7 % (Sherif et al., 2012) up to 40 % (Hammad and Abu-Hijleh, 2010), owing to the larger glazing façade areas in commercial buildings than residential buildings.

4.2. Active measures

Active design is a system or device that uses or produces energy. Solar panels, wind turbines, and district heating are examples of this type of measure (Spacey, 2017). As the Middle East has great potential for receiving solar radiation, the application of photovoltaic systems in a building is an option for electricity production, reduction of air conditioning loads, and enhancement of energy efficiency (Weber and Yannas, 2013).

In recent decades, Building-Integrated Photovoltaics (BIPV) received significant attention (Al-Saleh, 2009). It consisted of placing photovoltaic cells on building skins (Mujeebu and Subhi Alshamrani, 2015) to turn façades into elements that harness solar energy (Conde and Shanks, 2019). By equipping with energy storage systems, BIPV is able to provide and deliver energy when and where it is required. PV systems can produce both electrical and thermal energy with higher efficiency when developed and equipped with either active or passive ventilation to eliminate the heat and cool the PV module through the use of air or water as a medium (Gholami and Røstvik, 2020).

Improving the energy behavior of the envelope coupled to indoor thermal comfort and consequently reducing overall building energy demand along with electricity production from solar energy (Saretta et al., 2019) make BIPV an energy-efficient strategy for the building envelope retrofit (Mart et al., 2018).

BIPV system has been applied in different countries in Europe, America, and Asia, but it has not been widely used in the Middle East (Conde and Shanks, 2019). Studies on the impact of integrated PV systems on cooling and heating energy demand in Middle Eastern countries are lacking (Table S2 in Supplementary Material).

In KSA, rooftop PV systems occupying 25 % or 40 % of residential buildings roof areas covered 19 % and 29 % of the electricity demand, respectively (Dehwah and Asif, 2019). In Egypt, the installation of 900 m^2 panels on the roof of commercial buildings satisfied 40 % of the energy consumption (El Monem El Gindi, 2020). The efficiency of rooftop PV systems may be further improved (about 5 % to 10 %) by installing them above the cool roofs (Altan et al., 2019).

In an assessment of the configurations of rooftop PV panels under the Iranian climate, it was concluded that dividing the system reduced PV energy production. For example, a single array configuration obtained the highest energy production (Korsavi et al., 2018), and the combination of active strategies such as rooftop solar panels with passive ones leads to hybrid energy-efficient solutions for deprived off-grid vernacular buildings in Egypt (Dabaieh et al., 2016). Nonetheless, the application of PV systems is not a feasible option for KSA (Dehwah and Asif, 2019) or Iran (Korsavi et al., 2018) owing to current electricity tariffs. Similar results were found for all the Gulf Cooperation Council (GCC) countries, considering conventional electricity sources on a unit cost basis (Sharples and Radhi, 2013). GCC consists of six Middle Eastern countries, the UAE, Bahrain, KSA, Oman, Qatar, and Kuwait, all mainly coastal regions on the Persian Gulf, composed of deserts and humid coastal areas (Al-Maamary et al., 2017).

Semitransparent photovoltaic technology plays an important role, particularly for façade structures, and brings energy-saving advantages due to the reflection of more heat, which results in less air conditioning energy consumption (Alrashidi et al., 2020). A thermal simulation of two fully glazed high-rise buildings in the UAE predicted that thin-film photovoltaics, covering approximately 40 % of the façade, is the most promising solution regarding air conditioning load in the region (Bahaj et al., 2008).

An experimental energy analysis of a-Si semitransparent PV module integrated on a Trombe wall façade in a building in Izmir, Turkey, showed an increase in the system's thermal energy input compared to other types of BIPV. The average electrical and thermal efficiencies of semitransparent solar cells were about 4.5 % and 27.2 %, respectively (Koyunbaba et al., 2013). In another study in the UAE, energy improvements of the façade through the installation of semitransparent PV cells under different strategies (use of alternative ventilation modes and a different number of glass layers) were assessed. The results showed a reduction in sensible cooling demand of 1.5 % and 1.9 %, a drop in peak power of 4 % and 2.3 %, and an annual energy reduction of 2.5 % and 6 % for double and single inner layers, respectively (Elarga et al., 2016). Nonetheless, the ability of these PV cells to receive daylight inside through the façade was not studied in the Middle East (Joseph et al., 2019).

In Qatar, the poor conversion efficiency of PV panels and the very long payback period make the application of such technologies unreasonable when compared with the grid's low electricity cost (Abu-Rub et al., 2010). The studies which assessed the benefits of BIPV on the cooling load of commercial buildings in the UAE showed lower electricity production than calculated by estimation standards due to higher cell temperature, which reduces the system's production efficiency (Conde and Shanks, 2019). Furthermore, the study suggested better thermal performance of BIPV than conventional envelope materials; however, further modification to BIPV systems is needed to have higher performance in hot weather conditions.

In the UAE, the use of façade integrated photovoltaic systems onto commercial buildings demonstrated ratios ranging from 1/3 to 1/4 between PV energy production and energy savings (Radhi, 2010). The study emphasized that for the PV system to be cost-effective and the embodied energy payback time to be reasonable, the building's thermal performance improvement from adding an integrated PV system to the wall must be assessed. Therefore, the buildings' operational energy can reduce payback time to 6 y when applied in the northern façade and 3 y on the southern and western façades. Furthermore, the optimal tilt angle for a south-facing surface in the UAE is 24°. Another point to consider is that the estimated EPBT difference in UAE cities is due to the variation in temperature and relative humidity, as the efficiency of PV is lower in dry climates than in humid regions (Radhi, 2010).

In Kuwait, three scenarios were considered for public buildings to reach the net-zero target (AlAjmi et al., 2016). The scenario that only included the application of PV systems indicated that the generated energy exceeded the building’s total consumption. However, when analyzed monthly, from May to October, there was a shortage of energy production. The article suggested using the building façade to increase the PV's surface area or adding a hybrid system, such as combining PV panels and wind turbines, to prevent energy shortages. Hybrid systems may also satisfy a building’s electricity demand more effectively (Rekioua and Matagne, 2012). However, regarding PV’s thermal impact, the current BIPV system still cannot be considered the best option for reducing buildings’ energy needs due to their energy efficiency.

5. Energy-efficient cooling

In the Arab world, the building sector is responsible for an average of less than a quarter of all the sectors’ total energy (Alalouch et al., 2019). Air conditioning (AC) accounts for more than 60 % of the total (Elsarrag and Alhorr, 2012). AC and district cooling (DC) systems are two dominant systems used in the Middle East to meet cooling needs. Making improvements in the efficiency of these devices or replacing them with more efficient systems could play a significant role in reducing cooling energy demand. DC systems have multifarious advantages compared to on-site cooling systems installed in individual buildings.

In terms of technical, economic, environmental aspects, district heating/cooling systems were found to increase energy savings, reduce CO_2 emissions and reduce the cost of cooling demand in Middle East countries, particularly GCC countries. Reduction of electrical power consumption, higher efficiency, and savings during peak-period are the main reasons DC systems are preferred over on-site cooling systems (Eveloy and Ayou, 2019). In Kuwait, replacing package air conditioning units with DC systems contributed to reducing energy consumption and peak electrical power consumption by 54 % and 57 %, respectively. Another study in this region indicated a significant reduction in peak cooling demand (46 %) could be obtained if the DC system is used instead of the rooftop unit and variable refrigerant flow. From an environmental point of view, the higher efficiency and low-carbon energy sources could significantly decrease annual CO_2 emissions. For example, in Kuwait's case (Al-Qattan et al., 2014; Alajmi and Zedan, 2020), the reduction in annual CO_2 emissions was found to be 50 % and 52.8 %, respectively. Also, economic analyses demonstrated that the use of district cooling systems could reduce the cost of cooling demand (Al-Qattan et al., 2014) and reduce total cost over the cooling system's life cycle (Alajmi and Zedan, 2020).

6. Discussion

Climate change will impact the built environment in Middle East countries as global warming will increase cooling energy consumption. Nevertheless, there is a potential for the built environment to reduce its cooling demand by adopting passive design strategies and using renewable energy systems. A summary of the efficiency of the reviewed measures on both a building and urban scale under current and future climate conditions is presented in Table 3.

Table 3. The summary of efficient design strategies on an urban and building scale.

Scale	Design strategies	Impact on the reduction of energy consumption (present)/suggestions	Impact on the reduction of energy consumption (future)
Urban	Urban density or compactness Urban pattern (H/W) and configuration Greenery and reflective material Building orientation Building form	High urban density (compactness) Dense neighborhood (H/W of 12 recommended) as well as high canyon ratio Reflective pavements under the present condition and greenery (trees) in high-density areas are effective measures E/W orientation of buildings and open spaces Minimization of external surfaces (square shape)	Using reflective pavements with a high H/W ratio may not be as effective as when it is used under current weather conditions (other parameters have not been assessed under climate change scenarios in reviewed studies).
Building	Passive measures Thermal insulation Light or reflective coating Green roof and green wall Efficient glazing Shading devices Airtightness Cooling ventilation WWR	Reducing *U*-value (very efficient measure in residential buildings) High albedo coating and reflective painting (the most efficient measure in residential buildings) Multilayers glazing with low emissivity gas, low SHGC, and low *U*-value (the most efficient measure in commercial buildings)	Thermal insulation and thermal mass (low *U*-value envelope) are still efficient measures The efficiency of green roofs would decrease (3 %) under future climate scenarios compared to current conditions Double glazing has promising performance under future scenarios

		Application of different shadings (very efficient measure in commercial buildings) Reduction of air infiltration rate (lower than 0.5 ACH lowers indoor air quality Higher rate of night ventilation- natural ventilation combined with active systems - evaporative cooling in (hot-arid climate) Small WWR suggested (10 % for hot climate residential buildings)	Shading devices have an insignificant impact in the future for residential buildings
	Active measures	Application of rooftop PV and integrated PV can reduce building's air conditioning load	
	Energy-efficient systems	Replacing package air conditioning units with DC systems	

According to the results of the studies presented by Radhi (2009) and Andric et al. (2020), which analyzed the impact of passive strategies under future weather data, thermal insulation, and mass, in particular, may still be promising measures in the reduction of future energy needs for residential buildings in this region. Moreover, efficient glazing and green roofs could play a role in reducing cooling demand. At the same time, shading strategies have an insignificant effect on the reduction of future energy demand for residential buildings. However, each measure's characteristics need to be further studied and identified for each hot climate region (*e.g.*, an adequate amount of insulation or an optimized *U*-value).

The evaluation of several strategies on current building conditions revealed that passive cooling strategies, such as using highly reflective roofs, may reduce energy demand by 73 % (Mohamed et al., 2015). Furthermore, the application of shading devices and natural ventilation in commercial buildings may reduce energy consumption by up to 49 % (Bahaj et al., 2008) and 78 % (Ezzeldin and Rees, 2013), respectively. Using centralized systems instead of decentralized ones could benefit from energy savings and environmental impacts in many cases both for the tenants and the government. Also, photovoltaic systems could be feasible options for saving energy and reducing environmental impacts in Middle Eastern countries if the current thermal efficiency of photovoltaic cells increases and the cost decreases significantly.

The economic aspect of implementing retrofit measures is as important as their energy efficiency aspect. Therefore, some studies have considered sustainability and payback period, which refers to the ratio of Initial Cost of Investment to Annual Energy Saving to assess the viability of such measures (Dehwah and Asif, 2017). According to such an economic analysis, the payback period for applying different measures varies from 0.5 y (improvement of lighting system) to about 4.5 y (improvement of glazing efficiency) (Kharseh and Al-Khawaja, 2016). Application of all measures could result in a payback period of 1.5 y based on Qatar's current energy tariffs (Dehwah and Asif, 2017; Kharseh and Al-Khawaja, 2016). In the UAE, based on the investment and archived savings, the average payback period is 2.4 y for three retrofit strategies of efficient glazing, light roof coating, and airtightness (AlFaris et al., 2016). The payback period for different glazing types varies between 4.5 y to 8.5 y for a building in KSA (Dehwah and Asif, 2017).

However, the trade-off between energy savings and initial cost should also be considered. For example, tinted glazing has a higher potential in energy savings, but, from a cost-benefit analysis, reflective coating glazing provides more advantages (Taleb and Antony, 2020), while energy savings from dynamic louvers are slightly higher in terms of installation, operation, and maintenance. However, static louvers cost much less (Hammad and Abu-Hijleh, 2010). Other measures may have a longer payback period. For 20 y, windcatcher's cost-efficiency is higher than other measures, such as roof gardens and underground houses (Goudarzi and Mostafaeipour, 2017). According to a study on Iran's different climate regions, the green roof strategy's payback period would range between 25 y to 57 y (Refahi and Talkhabi, 2015).

Furthermore, a double-skin façade is economically infeasible (payback period of at least 59 y) for a country like Iran (Zomorodian and Tahsildoost, 2018), where the price of electricity is low, and the initial cost is high. Also, in a recent study, the payback period was estimated for a three-level energy retrofit plan, level 1 (low-retrofit), level 2 (medium-retrofit), and level 3 (deep-retrofit) on two types of residential buildings (villa and apartment) in KSA. The payback periods in the villa were 0.92 y, 8.37 y, and 25.15 y, and 0.60 y, 11.28 y, and 24.60 y for the apartment for the projection of levels 1, 2, and 3 of energy retrofitting, respectively. Therefore, according to the current scenarios, while deep energy retrofit (level 3) brings higher energy savings, it is not economically feasible for the existing residential buildings due to the current tariff rates in KSA (Ahmed and Asif, 2020). However, it should be noted that large-scale implementation of optimal retrofit programs for existing residential buildings in KSA could be cost-effective and bring a broad range of environmental, social, and economic benefits (Krarti et al., 2020).

7. Conclusion

Global warming contributes to the growth in energy consumption and greenhouse gas emissions of the built environment in warm climate regions. The temperature rise exacerbates the buildings' cooling demand in the Middle East region.

The most effective cooling passive measures in residential buildings are highly reflective roofs, natural ventilation, and thermal insulation. However, in commercial buildings, the role of natural ventilation, efficient glazing, and shading devices are more significant for cooling energy savings. While BIPV may reduce energy demand from the grid, the high outdoor air temperature and the purchase cost of PV are the two main barriers to using renewable energy systems. Also, replacing on-site air conditioning systems with centralized ones may save energy in the region due to higher efficiency.

Denser neighborhoods with higher building height to street ratio reduce cooling needs at the city level due to self-casting shadows. The east-west building orientation and the lower surface-to-volume ratio showed a higher potential in energy savings in Middle East countries. Implementing most passive cooling measures is economically feasible in these countries due to their short payback period. Nonetheless, the highly subsidized fossil fuels and low electric energy tariffs are the main obstacles to the widespread use of renewable energy systems.

Ultimately, it is worth mentioning the lack of studies estimating the efficiency of building design measures in Middle Eastern countries under future climate conditions. Indeed, most of the reviewed papers only considered the current weather condition and ignored the impact of climate change on the built environment, which energy use could overestimate measures' efficiency and lead to more energy consumption and GHGs emissions. Thus, there is an urgent need for more studies that strengthen the understanding of how the built environment will perform in hot-dry climates.

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CRediT authorship contribution statement

Nazanin Azimi Fereidani: Conceptualization, Writing – Original Draft, Methodology, Formal Analysis, Data Curation, and Visualization. **Eugénio Rodrigues:** Conceptualization, Methodology, Writing – Original Draft, Writing - Review & Editing, Visualization, and Supervision. **Adélio Rodrigues Gaspar:** Conceptualization, Methodology, Review & Editing Supervision.

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