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Climate change implications for environmental performance of residential building energy use: The case of Qatar

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Abstract

Building energy demands in the future could increase due to the climate change driven increase in outdoor temperatures. Gulf countries characterized by extreme climate and dependency on fossil fuels would be especially vulnerable to such impacts. Considering that in such countries about 80% of energy produced is used for cooling services, an increase in cooling demand would affect both building environmental impact and grid stability. The main scope of this study is to quantify such implications by considering the residential sector of Qatar as a case study. A representative building of the national building stock was selected, and energy consumption was modelled for present and forecasted weather conditions. The results indicated that in the future, heat waves will occur more frequently, with a higher intensity and a longer duration. Consequently, building energy consumption will increase for up to 30%. Such increase in energy demand would result in higher CO₂ emissions, water and fossil fuel depletion rates, as well as increased impact on already strained local marine ecosystem. In order to mitigate such impacts, New regional environmental policies should be developed for large-scale renovation of the existing building stock and installation of renewable energy systems in order to mitigate the environmental impacts.

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Keywords: Climate change; Buildings; Energy consumption; Environmental impact

1. Introduction

Due to their stationary nature and dependence on complex, internetworked infrastructure, dense urban ecosystems such as cities are highly susceptible to climate change impacts. Such dependence is further amplified by the rapid population increase and migrations from rural to urban areas, driven by the economic growth. For example, the population in Qatar grew from 676,498 in 2002 to 2,529,048 in 2018 (out of which 92% live in the capital city, Doha), which is an increase of 245% over a 16-year period. Such trends in rapid population growth, urbanization, increasing complexity and reliance on technology puts Qatar vulnerable to significant climate change risks.

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The climate change impacts are both short-term and long-term. Within short-term impacts, extreme weather events such as storms, floods and landslides can be considered. On the other hand, gradual changes in outdoor air temperature and sea level rise can be defined as long-term impacts. Considering the geographical position of Qatar, local climate properties and predictions from Intergovernmental Panel on Climate Change (IPCC) that heat waves will occur more frequently and have a longer duration in the future [1], the long-term impacts present a higher risk on regional level.

Gradual changes in weather patterns would have a significant impact on built environment, its energy consumption and related energy systems [2,3]. Due to the significant difference between the outdoor air temperature and indoor comfort temperature in hot climates (in summer months, outdoor temperatures in the Middle East frequently reach over 40 °C, while the indoor temperature is set to 18–20 °C), energy use for cooling is responsible for majority of energy end-use (it is estimated that up to 80% of total energy produced in Middle Eastern countries is consumed by the cooling systems [4]. Even under current climate conditions, these countries are facing challenges to cover their electricity demand over summer months [2,4–6], experiencing recurring grid burnouts and consequent power blackouts. Considering the climate-change driven increase in outdoor temperatures, such events could become more frequent and have a longer duration. Such stress on grids would have both societal and economic impacts. Furthermore, cooling services are necessary for achieving basic comfort conditions, blackouts would significantly affect the everyday life of local population. Additionally, the current economy of such countries is based on the export of fossil fuels, and power outages would significantly impact production and service downtime of the refineries [5].

The abundance of fossil fuel resources in Gulf countries, such increase in electricity demand could be covered by installing additional production capacities. However, additional fossil-fuel based electricity production would increase already significant carbon footprint of these countries, which would consequently result in lower air, land and water quality [6,7]. Additionally, an increase in self-consumption and depletion rates of natural resources would reduce the amount of resources available for exports, hurting the local economy.

The main scope of this study is to assess the rate of climate change-driven increase in residential building energy demand in rapidly developing urban environments of Gulf countries and assess the consequent environmental impacts. An interdisciplinary methodology framework is developed and applied on the residential stock of Qatar as a case study. Finally, based on the impacts assessed, potential mitigation measures are proposed and discussed.

2. Methodology

In order to assess the impact of climate change on energy systems, a synergy between five research methodological frameworks is required: (1) regional climate change modelling, (2) building energy modelling, (3) impact interpretation, (4) mitigation scenario development and (5) implementation. The outline of the interdisciplinary methodology framework developed within this research project is presented in Fig. 1.

- Regional climate modelling — Future weather data for the case study location has been forecasted by using the CCWorldWeatherGen tool, which was initially developed by the research group from the University of Southampton [8]. The software requires two main inputs: Typical Meteorological Year (TMY) in.epw format as a reference weather data, and output simulation files (for the A2 family of IPCC (Intergovernmental Panel on Climate Change) scenarios) from the coupled HadCM3 Atmosphere–Ocean Global Circulation Model (AOGCM), developed at the Hadley Centre (London, United Kingdom);
- Building energy demand modelling — modelling energy demand of the national residential building stock was conducted in several steps: architectural profiling, case study selection, building model creation and energy demand modelling. Architectural profiling of the national building stock was performed in order to identify building type that can be considered as a representative for the national building stock. Based on the type identified, case study building is selected based on the previously defined criteria during the stock profiling. Finally, a 3D computer model of the building is developed for which the energy demand is simulated. In this study, DesignBuilder (v.5.4) [9] tool was used in order to create a 3D model, while energy demand simulations were performed by using integrated EnergyPlus (v.8.6) [10] simulation engine (developed by the U.S. Department of Energy). Reference building data (geometrical and thermal properties) was obtained from the contractor who built the property and building owner;

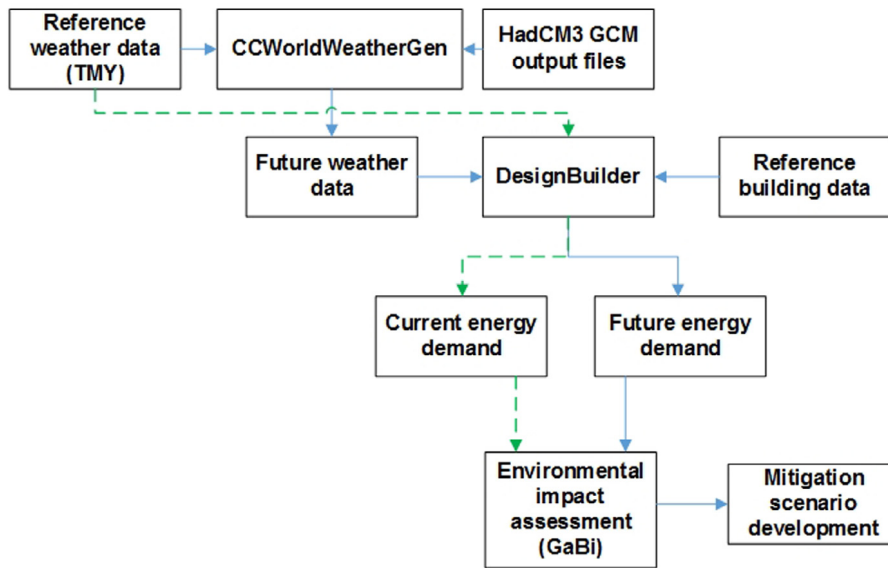


Fig. 1. Developed methodology framework.

- Impact interpretation — in order to assess the annual environmental impact of building energy consumption, environmental impact factors (ReCiPe methodology) for the case study location (Qatar) were used, available within the GaBi [11] life cycle assessment (LCA) software suite. The impact factors from the software were obtained in values per kWh of electricity consumed (thus grid transmission losses were taken into account), and focus was on the contribution to climate change and depletion of local natural resources;
- Mitigation scenario — the scenario for mitigating the impacts assessed is developed based on the regional societal and economic aspects and long-term perspectives;

3. Case study

Within this study, the residential sector of the State of Qatar is considered. Qatar is characterized by the hot desert climate and one of the highest population and urban development growth rates in the world. Moreover, the role of residential building sector in achieving long-term sustainability goals has already been recognized in national development plans such as Qatar National Vision 2030. The majority of local population (92%) resides in its capital city, Doha. The results from the architecture profiling and advices from local real estate experts suggested that Doha's residential urban environment has been characterized by residential villas, situated individually or grouped within the residential compounds. An existing property that fits the description has been selected for further study, due to its geometry and construction characteristics. The property consists of an individual two-storey single-family villa, with an overall floor surface of 327 m² (ground floor, first floor and penthouse) and 29 m² external kitchen. The design of the property is given on Fig. 2 (photos of the property are not presented in order to protect the privacy of the owner). Building construction properties were obtained from the project documentation and material specification from manufacturer data sheets. As a reference weather data, a TMY (Typical Meteorological Year) weather file for Doha was used, from the ASHRAE International Weather for Energy Calculation (IWEC2) database [12].

4. Results

4.1. Climate change modelling

The outputs from climate modelling are presented on Fig. 3. Under current (reference/TMY) conditions, temperatures over 38 °C occurred over 700 h (8% of all (8760) hours) during the year. In 2020, the number of

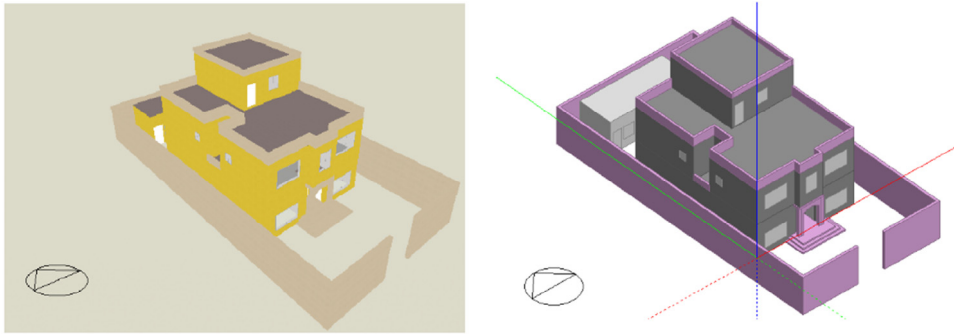


Fig. 2. Architectural (left); energy model (right) of the studied property.

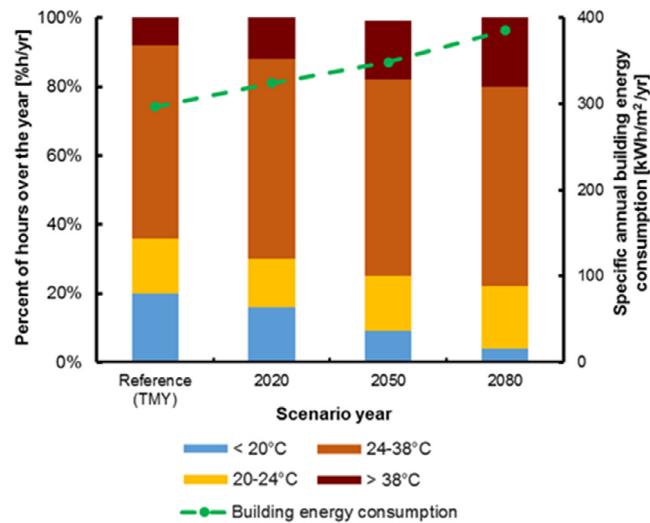


Fig. 3. The results from climate and building energy demand modelling.

hours with such temperature increased up to 1139 h (13%), while the increase rates for 2050 and 2080 were even higher — 1490 h (17%) and 1840 (21%), respectively. The number of hours within the temperature ranges of 24–38 °C and 20–24 °C remained stable, increasing to up to 2 percentage points or 175 h. On the other hand, the number of hours with temperatures below 20 °C decreased significantly, from 20% (1752 h) to solely 4% (350 h) in 2080. Thus, as previously assumed, heat waves in the future will occur more frequently, have a higher intensity and last longer.

4.2. Building energy consumption increase and impact on energy systems

Climate change driven increase in building energy demand is also represented on Fig. 3 (green dashed line). The specific building annual energy demand increased for 9% in 2020 compared to reference (TMY) year, while in 2050 and 2080, energy demand increased for 17% and 30%, respectively. Such escalation in building energy consumption would result in steep peak load increase on electricity grids and urban energy systems (district cooling systems). The increase would change the ratio between peak load and base load energy production units and would require the installation of an additional production capacity and an associated increase in investment costs. Additionally, considering the fossil fuel intensity of energy systems in Gulf countries, consumption increase would result in an additional stress for the environment, which is discussed in detail within the next section.

Table 1. Building annual energy consumption related environmental impacts.

Impact category	Reference (TMY)	2020	2050	2080
Climate change contribution [kg CO ₂ eq.]	5.89E+04	6.43E+04	6.91E+04	7.65E+04
Fossil fuel depletion [kgoe]	2.67E+04	2.92E+04	3.14E+04	3.47E+04
Water depletion [m ³]	1.19E+04	1.30E+04	1.40E+04	1.54E+04
Marine ecotoxicity [kg 1,4-DB eq.]	5.78E–02	6.32E–02	6.79E–02	7.51E+02

4.3. Environmental impact

The results of environmental impact assessment related to annual building energy consumption are given within Table 1. Four impact categories were selected for analysis based on the scope of this study and aspects critical for the case study location. Since the scope of this study is based on the analysis of climate change impacts and their consequences, climate change contribution (in kg CO₂ eq.) of the studied system is observed, since further changes in the climate system would result in even higher outdoor temperatures than within the scenarios used within this study. Qatar's economy is largely based on fossil fuel exports, fossil fuel depletion (in kg oil equivalent) is studied. Water depletion was also considered because of freshwater is scarce in Qatar and is an essential nature resource. Due to such water scarcity, the majority (99%) of potable water is produced by seawater desalination, which has significant impact on local marine ecosystems. In addition, marine ecotoxicity was also considered as an impact category (expressed in kg 1,4-DB (1,4-dichlorobenzene) to account for the local sensitivity of the local marine ecosystem. The findings indicated that the increase in energy demand would cause an additional 17.5 tCO₂ eq. to be emitted, 8 toe fossil fuels and 3551 m³ of water consumed, as well as 20 g of 1,4-DB released to local marine ecosystem annually. Considering that these figures present the impact of energy consumption increase for a single villa on an annual level, and that there are 80,573 such villas in Qatar, the impact on the national scale would be staggering. Thus, adequate mitigation measures have to be developed.

4.4. Mitigation measures

In order to mitigate the increase in environmental impacts, two approaches could be considered: addressing the building energy efficiency or the sustainability of energy production systems. Namely, by renovating the building stock and improving the thermal performance of the building envelope, heat transmission rate between the indoor and outdoor environment could be reduced, consequently lowering the building energy demand [13–15]. Multiple studies within the bibliography indicated the environmental and economic benefits of building envelop renovation [16–19]. However, large scale renovation of national building stock proved to be challenging even in developed countries [2]. On the other hand, by replacing fossil-fuelled energy production units with renewable energy ones, both current and increased emissions in the future could be mitigated. Nonetheless, despite the abundance of renewable energy resources (solar radiation for PVs, coastal areas for wind and tidal farms), the use of renewable energy in Gulf region is extremely rare [20], mostly since they are not considered economically feasible (due to the abundance and low cost of fossil fuels). Thus, new regional environmental policies should be developed in order to increase the penetration of renewable energy systems.

5. Conclusion

The difference between the outdoor air temperature and indoor temperature could increase as a result of climate change and consequently increases the energy demand for cooling in Qatar. The surge in cooling demand would increase the electricity demand peaks during heat waves on a grid that is already under significant pressure. Apart from increasing the risk from grid failures and power outages, additional consequences would be the increase of natural gas self-consumption (and thus lowered exports) and increase in building environmental impact.

The results from climate modelling indicated that over the next 60 years, the intensity, frequency and duration of heat waves would significantly increase, with temperatures surpassing 45 °C occurring over 21% (1840 h) of the year. Consequently, building annual energy demand increased for up to 30%. Moreover, such increase would result in higher CO₂ emissions (up to 17,5 tCO₂eq per household on an annual level). Furthermore, the increase

would inevitably contribute to the depletion of local fossil fuel and water resources, as well as to the damage of local marine ecosystem, which is already under strain due to presence of water desalination plants.

The increase in environmental impacts could be mitigated either by renovating the building stock and improving its energy efficiency, or substituting fossil-fuelled energy production units with renewable energy systems, such as PV plants, wind farms and tidal plants. However, in order to integrate such solutions on a large scale, new environmental policies should be developed, that consider societal and economic aspects specific for the Gulf region.

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