Predicting the Impact of Climate Change on Operational Energy and Thermal Comfort in the Housing Stock of Jordan

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Abstract. The Intergovernmental Panel on Climate Change (IPCC) has projected a significant increase in temperature by 2050. In regions characterized by harsh summer climates, such as Jordan, this would have negative effects on energy and thermal performance in the existing housing stock.

This study aims to generate a predictive model that assesses the impact of future climate change on both operational energy (OE) use and thermal comfort expected in Jordan's housing stock by 2050. To do so, a thermal simulation of a Jordanian housing stock model using a future weather file is used. Next, the impact of changing climate conditions on the thermal comfort of residents is investigated. A Predicted Mean Vote (PMV) thermal sensation scale from ASHRAE 55 based on Fanger Comfort Model, and Predicted Percentage of Dissatisfied (PPD) are utilized to assess the level of comfort in the selected dwellings with mechanical energy systems. The CIBSE TM59 approach is used to predict the overheating risk in naturally ventilated dwellings.

In the context of 2050 data analysis, discomfort hours increase in naturally ventilated archetypes, while the mechanically ventilated and air conditioned archetype experiences a notable rise in PMV (3.8) and PPD (89%) during summer., While total operational energy show a noticeable decline across the entire stock, ranging from 18% to 33%, future climate conditions may lead to increased energy consumption for cooling in housing stock if mechanical cooling is used . This study will contribute to the local discourse on sustainable urban development in the face of climate change.

Keywords: Operational energy, Climate change, Thermal comfort, Housing stock.

1 Introduction

Balancing energy efficiency and occupant well-being is crucial for sustainable development in the face of evolving climate patterns [1] [2]. Climate change poses significant challenges to the built environment, particularly in regions with diverse climatic conditions such as Jordan. This study delves into the intricate interplay between climate change, OE, and thermal comfort in the housing stock of Jordan. The International Energy Agency (IEA) projects that, by 2050, approximately two-thirds of the global population could rely on air-conditioning, resulting in a threefold surge in the worldwide energy demand for space cooling in comparison to current levels [3].

Studies have shown that climate change can have a profound impact on thermal comfort and energy usage in buildings [4] [5]. In the face of Climate Change, policy efforts around the world for all new buildings to operate at net zero CO_2e by 2030 have increased in recent years [6]. The global increase in outdoor temperatures must be addressed in order to eliminate the risk of indoor overheating conditions [8] [9].

Some of the commonly used thermal comfort standards are ASHRAE 55, ISO 7730, EN 15251, which are based on the predicted mean vote (PMV) and the predicted percentage dissatisfied (PPD) models. These models relate the thermal comfort indicators to the physical parameters of the thermal environment, such as air temperature, radiant temperature, humidity, air velocity and globe temperature, and the personal factors of the occupants, such as clothing and activity level [10] [11].

CIBSE TM59 sets out a methodology for assessing the risk of a home overheating, broken down into criteria for homes that are predominantly naturally ventilated, those that are predominantly mechanically ventilated and communal corridors [12]. CIBSE TM59 recommends that peak bedroom temperatures should not exceed a threshold of 26 ◦C [13], which can be referred to as overheating. Practically, the air temperature is utilized to assess overheating by measuring humidity, absence of airflow, radiant heat, and duration of heat exposure for the region [14]. These periods of unusually hot weather in the summer are classified as heatwaves [15].

Results of CIBSE TM59 analysis using DesignBuilder follow 2 criteria: criterion A for the hours of exceedance for living rooms, kitchens and bedrooms, and criterion B for number of hours of exceedance for bedrooms only. In criterion A, the hours of exceedance shall not be greater than 3% of occupied hours during the period May to September. While criterion B is passed if the operative temperature is exceeded for less than 32 hours [16]. Jordan has three climate regions: deserts, mountains and Jordan Valley, and cities are distributed following them. Ma'an, Mafraq represent Desert region, Amman, Zarqa, Irbid, Balqa', Madaba, Ajloun, Jerash, Karak represent the Montain and Valley from the sea of Galilee to the dead sea, Wadi Araba, and Aqaba are the Jordan Vallley region [17] [18].
This study aims to address the urgent need to predict the dual impact of climate change on OE use and thermal comfort within Jordan's housing stock.
By doing so, the study seeks to provide valuable insights that can inform sustainable building practices and policy decisions in the face of a changing climate.

2 Methodology

Figure 1 represents the study method to estimate OE and evaluate the thermal comfort expected in Jordan's dwellings by 2050.

2.1 Dynamic simulation: Energy demand and Thermal Comfort (TC)

The starting point for the methodology of this work is using a most prevalent archetype model previously developed for environmental characterization following the four categories shown in Figure 2, uncertainty analysis of this model was described in depth in a previous study [19].

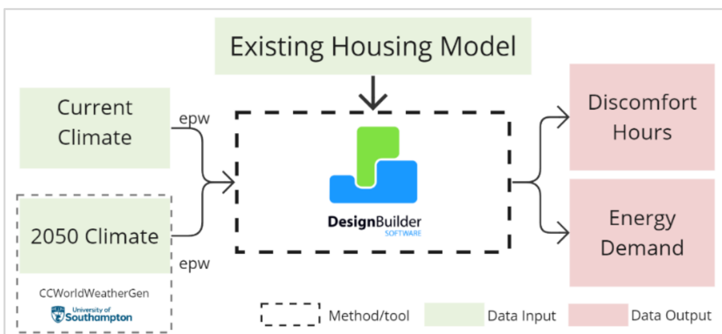

Fig. 1. Methodology scheme - Energy demand and thermal comfort assessment.

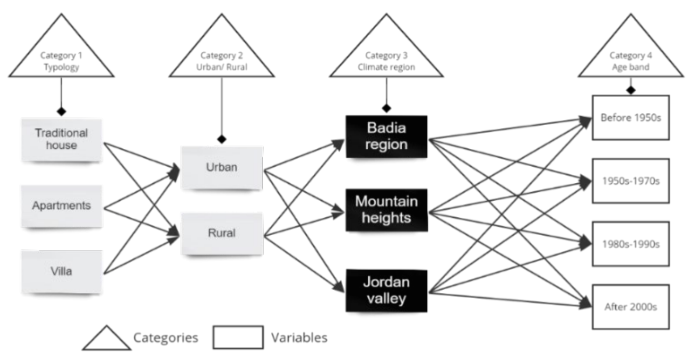

Figure 2. Flow-chart of the current Jordanian housing stock *[19]*.

The Apartment-Urban-Mountain archetype models, AUM1 (1950s-1970s), AUM2 (1980s-1990s), and AUM3 (After 2000s), represent 72% of the total entire stock energy consumption and 69% of the total area of the entire housing stock in Jordan. The models' envelope and energy characteristics required for energy analysis are illustrated in 'Appendix 1'. Table 1 illustrates the energy systems and fuel type used for heating and cooling of the housing archetypes in Jordan.

Table 1. The area of AUM archetypes from the total share of dwellings in Jordan and energy systems characteristics.

Arche-type	Total Area (m^2)	Share of total area (%)	Heating		Cooling	
			Type/ Efficiency	Fuel	Type/ Efficiency	Fuel
AUM1	35,676,235	11%	Kerosene heater 0.65	Kerosene	N/A	
AUM2	62,433,411	25%	Gas heater 0.70	LPG	N/A	
AUM3	80,271,529	37%	Electric heater 1.00	Electricity	AC 2.4	Electricity

The dynamic simulation approach using DesignBuilder – an interface software for EnergyPlus, is used to estimate the energy demand and discomfort hours of models. The assessment of comfort levels in the AUM3 archetype involves the application of PMV thermal sensation scale derived from ASHRAE 55 based on Fanger Comfort Model and PPD. PMV values indicate the thermal sensation felt by occupants. Negative PMV values denote a sensation of cold, while positive values indicate warmth. In AUM1 and AUM2, CIBSE TM59 is used as a methodology for assessing the risk of overheating in future summer climate.

2.2 Future climate scenario

The Sustainable Energy Research Group (SERG) at Southampton University has introduced a Microsoft® Excel tool, named the 'Climate Change World Weather Generator (CCWorldWeatherGen)' [20]. This tool enables users to generate prospective weather files for global locations across three temporal segments: 2020s, 2050s, and 2080s. Tailored for the conversion of EPW file templates, the tool consistently produces future weather data in the EPW format, facilitating seamless integration with Building Performance Simulation (BPS) tools. For a comprehensive understanding of the climate parameter generation for EPW future weather data, readers are encouraged to explore the works of [21] and [22].
The WorldWeatherGen tool is used to create future weather files reflecting anticipated climatic changes in Jordan. Thermal simulation using a future weather file of the *Mountains* climatic region of Jordan is used to evaluate how climate change may influence operational energy use of dwellings in Jordan.

3 Results

The analysis results present the investigation into TC and OE variations between current and future weather files (2050s) for residential buildings in Jordan. Employing the PMV comfort analysis and discomfort hours as key metrics, the study unveils the impact of changing weather conditions on occupants' comfort in AUM3 archetype (Figure 3), and adaptive TC using CIBSE TM59 in AUM1 and AUM2 (Figure 4, and 5), and energy consumption (Figure 6) for the current conditions and projections for the year 2050.
Figure 3 illustrates the dynamic relationship between TC levels and discomfort hours across different climatic scenarios for AUM3 archetype. The 2050 data generally indicates an increase in discomfort hours. In analyzing the adaptive TC of predominantly naturally ventilated homes, AUM1 and AUM2, according to TM59 standards for the years 2020 and 2050, it's evident that several zones consistently fail to meet the specified criteria. Notably, across different housing archetypes, bedrooms, entrances, guestrooms, kitchens, and living rooms, consistently fall short in both the current and projected years. For instance, in first floor at AUM1, while Criterion A increases from 17.44% to 36.91% from 2020 to 2050, Criterion B shows a substantial increase from 32.5 hours to 750.5 hours, resulting in a continued failure. Similar trends persist across various zones and AUM2 archetype, indicating a persistent challenge in achieving adaptive TC. In 2020, many zones in AUM2, including bathrooms, bedrooms, guest rooms, and living rooms, failed to meet the set criteria, indicating a lack of TC, especially on both third floor and the fourth floor. The problem of such thermally uncomfortable homes in Jordan mainly lies in two factors; thermally uninsulated buildings, low quality windows and doors [23].
Notably, in AUM3 there is a general trend of increasing PMV and PPD values in the future, indicating a potential rise in thermal discomfort. For instance, in January, the PMV increased from 1.4 to 1.6, and PPD remains at 54%, suggesting a moderate level of discomfort that persists in the projection. March sees a more substantial shift, with PMV rising from 1.8 to 2.2 and PPD increasing from 59% to 65%. The summer months exhibit the most significant changes, with August showing a substantial increase in PMV from 2.7 to 3.8 and

PPD rising from 77% to 89%. These projections indicate a significant impact on TC in the future, particularly during warmer months, necessitating adaptive strategies to mitigate discomfort and enhance indoor conditions.

Figure 6 reveals a forecasted change in OE (kWh/m² per annum) in Jordan houses by 2050. It represents the energy consumption for heating in AUM1, AUM2, and AUM3. In AUM3, there is a slight increase in energy consumed for cooling. Figure 6 presents the decrease in annual OE in 2050.

There is an observable reduction in OE consumption across the entire housing stock from 2020 to 2050, with 23% in AUM1 from 54 kWh/m². Y to 44 kWh/m². Y, 49% in AUM2 from 85 kWh/m². Y to 57 kWh/m². Y, and 17% in AUM3 from 77 kWh/m². Y to 65 kWh/m².Y. This decline is primarily attributed to the lowered heating consumption.

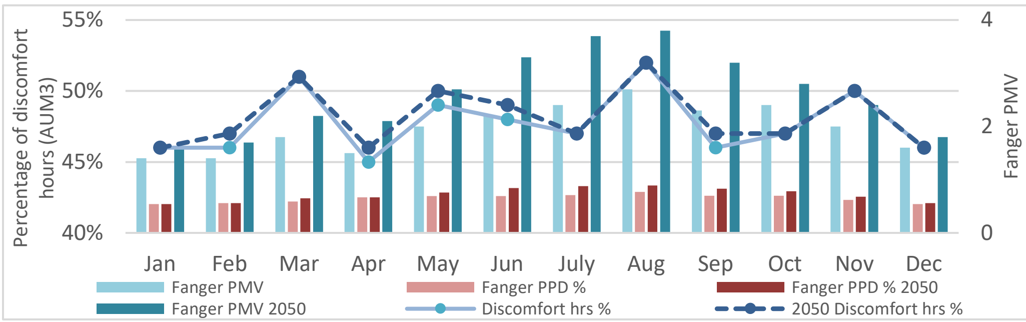

Figure 3. Average monthly Fanger's PMV and discomfort hours for AUM3 archetype.

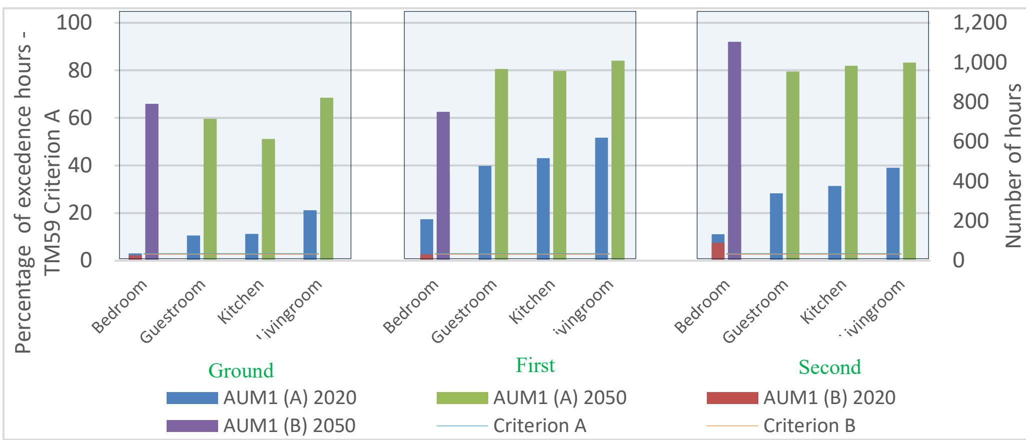

Figure 4. Adaptive thermal comfort analysis for 3 floors of AUM1 archetype employing CIBSE TM59

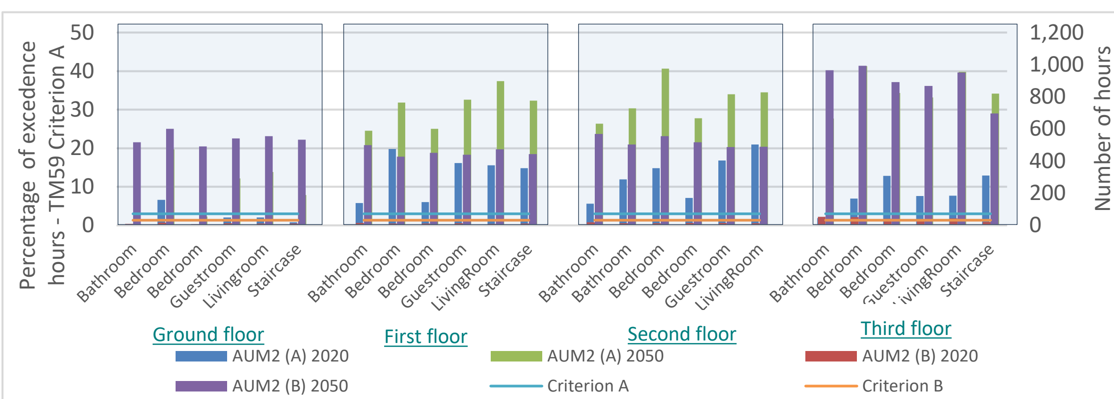

Figure 5. Adaptive thermal comfort analysis for 4 floors of AUM2 archetype employing CIBSE TM59

4 Discussion

The results point to the significance of adopting adaptive thermal models and passive retrofitting measures to enhance both energy efficiency and TC. Addressing these challenges requires a multidisciplinary approach, involving collaboration between policymakers, architects, and the local community. The improvements may include energy efficiency measures at the building level or upstream. The AUM1 and AUM2 archetypes encounter an increase in thermal discomfort, suggesting the potential necessity for the implementation of cooling systems to alleviate adverse conditions. Figure 7 represents the risk for energy performance when using mechanical cooling systems in 2050 climate. Passive cooling measures offer effective ways to mitigate the risk of overheating in buildings and the risk of energy performance if using mechanical systems in the face of climate change.

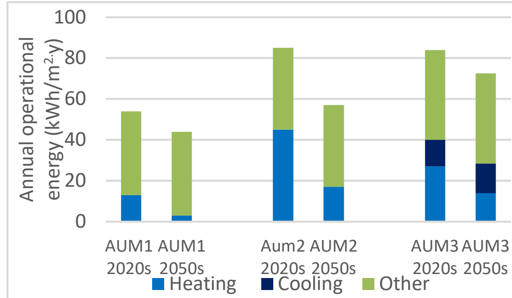

Figure 6 The operational energy of AUM archetypes in current '2020s' and future '2050s' climates.

Strategies such as improved building envelope, increased natural ventilation, and reflective roofing can help reduce the reliance on energy-intensive air conditioning systems [24]. Extended ventilation hours, night ventilation and thermal mass are all passive strategies to improve the TC of dwellings. However, without implementing these passive measures, the widespread use of air conditioning not only poses immediate energy use challenges but also contributes to long-term environmental impacts, including excess emissions.
This underscores the importance of integrating passive cooling strategies alongside active measures to ensure sustainable cooling solutions. By doing so, not only can we mitigate the risk of overheating in buildings, but also address the hidden energy risks associated with escalating demand for air conditioning, thereby supporting decarbonization efforts in a changing climate.
The observed increase in PMV and PPD values in AUM3 in summer, particularly in August, signifies a pronounced impact on thermal comfort. This necessitates urgent attention and adaptive strategies to mitigate the adverse effects. The findings highlight the urgency of developing interventions to address the evolving TC requirements of indoor spaces. Potential strategies may include the integration of energy-efficient HVAC systems, and adaptive building design to counteract the anticipated rise in discomfort hours. Moreover, this could be extended to future work to investigate refurbishment scenarios to improve OE and TC in a future climate.

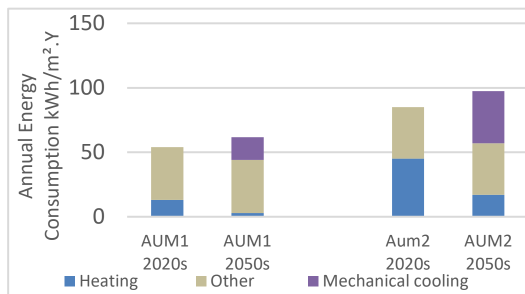

Figure 7 The risk of energy consumption using mechanical cooling for AUM1 and AUM2 dwellings.

5 Conclusion

This study delves into the intricate interplay between TC and OE use, examining the disparities between present conditions (2020s) and future projections (2050s) for housing stock in Jordan. Utilizing PMV Fanger TC analysis and discomfort hours as pivotal metrics, the research sheds light on the profound impact of evolving weather patterns on the well-being of occupants and the corresponding energy consumption patterns. The analysis of AUM1 and AUM2, under TM59 standards for 2020 and 2050 reveals consistent failure across various zones and housing archetypes, indicating challenges in achieving TC. Conversely, in AUM3 exhibits an increase in PMV and PPD values. The disparities, especially evident in the summer months, emphasize the need for adaptive strategies to counteract discomfort and enhance indoor conditions.
The findings underscore the necessity for proactive measures and policy interventions to create resilient, energy-efficient homes that prioritize the well-being of occupants amidst a changing climate.

Disclosure of Interests. The authors have no competing interests to declare that are relevant to the content of this article.
Appendix A: https://drive.google.com/file/d/1qcu0euXdjpK1KmaOfPWix6sijCcHv79A/view?usp=sharing

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