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Developing a housing stock model for evaluating energy Performance: The case of Jordan

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ABSTRACT

The housing stock is the long-lasting component of the settlement structure. The dwellings make up 72% of buildings and consume around 40% of the primary energy in Jordan. The government in Jordan aims to meet the goals of Paris Agreement by 2050 toward net zero carbon. Considering its importance, this study aims to provide an approach for developing a housing stock model for Jordan to evaluate energy consumption of the residential sector at national level, as a baseline for improving the energy performance of the entire housing stock.

A bottom-up approach is used to generate models of the Jordanian housing stock based on available buildings datasets. The generated 21 archetype models are analysed and used to evaluate the energy consumption of the national housing stock. Two archetype models represent the highest contribution, more than 80%, of annual energy use from the entire housing stock. The uncertainty analysis figures out that the 8.3% discrepancy between the baseline results and the measured data, for the entire stock, can be explained by the expected variation in input data.

The study can provide policymakers with valuable insights into the energy performance of Jordan's housing stock and inform the development of effective policies and strategies to reduce energy consumption and promote sustainable development. For example, it can assist in identifying the most effective interventions for refurbishment of different archetypes in the current stock, and the improvements required in new-build dwellings and thereby facilitate the transition to a low-carbon building stock in Jordan.

1. Introduction

The operations of buildings account for 30 % of global final energy consumption and 26 % of global energy-related emissions [1]. The residential sector in Jordan accounts for approximately 40 % of the primary energy and 46 % of the country's total electricity consumption [2], making it a significant contributor to greenhouse gas emissions and air pollution. Improving the energy performance of the housing stock is crucial for achieving national energy efficiency goals and reducing environmental impacts. To achieve this goal, a comprehensive understanding of the energy consumption patterns of the entire housing stock is essential.

The energy sector faces various challenges, including the lack of diversity of energy suppliers and the need to reduce dependence on fossil fuels [3,4]. 92 % of Jordan's principal energy sources are imported from Arab nations including Egypt, Syria, and other Gulf states [5]. In 2011, due to natural gas disruption and unreliability of gas supplies from Egypt, Jordan took a series of measures to use energy rationally at government institutions and public facilities and urge the citizens to cooperate in energy conservation, as Jordan's power plants were forced onto their costly heavy fuel oil and diesel reserves [6]. Table 1 presents Jordan's primary energy sources (2018–2025) [7]. The increase in energy demand in Jordan is expanding at a pace of 3 % annually [8].

The Jordanian government is committed to reducing the country's dependence on fossil fuels and increasing the contribution of renewable energy to its energy mix [9]. The national energy strategy for 2020——2030 sets a target of increasing the renewable energy share to 14 % by 2030 [5].

Jordan's Committee for Nuclear Strategy, established in 2007, outlined a program for nuclear power to produce 30 % of electricity by 2030, and to facilitate exports [10]. The target of Jordan Atomic Energy Commission (JAEC) is to transform Jordan into a net electricity exporter by 2030, following the strategy of exploiting national uranium assets, promoting public/ private partnerships, developing spin-off industries, and enabling competitive energy-intensive industries [11]. Jordan has also enormous solar energy potential, with average solar radiation of

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Table 1
Jordan primary energy sources (2018–2025).

	2018	2020	2025
Crude Oil and Products	54 %	51 %	50 %
Coal and coke	3 %	4 %	4 %
Renewable Energy	8 %	10 %	6 %
Natural Gas	35 %	30 %	8 %
Electricity imports	0 %	0 %	0 %
Oil shale		5 %	10 %
Nuclear			22 %

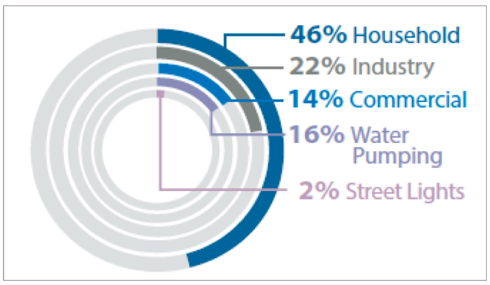


Fig. 1. Sector distribution of final electricity consumption in Jordan (2018), [16].

between 4 and 8 kWh/m^2, implying a potential of 1,400–2,300 GWh annually [12]. As of 2020 carbon intensity of the electricity grid in Jordan was approximately 0.435 kgCO_2e per kWh of electricity generated [13]. The National Energy Sector Strategy (2020–2030) is a plan that sets a roadmap to increase self-sufficiency through the utilization of domestic natural and renewable sources, reduce energy consumption by improving the energy efficiency measures in different sectors, and reduce the carbon dioxide emissions by 10 % by the year 2030 [14]. Jordan was aiming to have two 1000 MWe nuclear power units in operation by 2025 but is now considering the use of small modular reactors instead [15].

The building sector in Jordan is a vital part of the country's economy, although it still faces several challenges. One of the challenges is the need to adopt sustainable construction practices. As the Jordanian government issues building licenses, construction is moving rapidly, and Jordan's building stock is growing by 4–5 % annually [16].

So far, there have been some endeavours to reduce the carbon emissions of the housing stock in Jordan, however, this has not yet been tackled in that scale at the national level. This paper aims to provide a methodology for generating a comprehensive housing stock model used for evaluating the energy consumption within the national residential sector. This stock model can then be used as a baseline for improving the overall energy efficiency to meet the local recommendations and targets toward net zero carbon emissions of the housing stock in Jordan.

2. Literature review

2.1. Jordan residential sector profile

Jordan's capital, Amman, accounted for 46 % of the total dwellings in Jordan in 2019 and represented the largest share of construction [17]. Stimulated by demographic growth and arrival of several waves of refugees, Jordan's private sector produced 1.1 million dwellings between 2004 and 2015 [18]. With half of these apartments built in Amman, many of them are spacious and unaffordable [19].

Since the residential building sector is the highest electrical energy-consuming sector in Jordan [20], as shown in Fig. 1, this highlights the need for energy-efficient residential buildings in the country. The evaluation of near-net-zero-energy building strategies has been conducted in Jordan, with a focus on the residential sector [20].

The lack of energy-related analytical data and the disintegration of

Table 2
Benefits and limitations of bottom-up and top-down modelling methods (Adapted from [25]).

Characteristics	Top-down	Bottom-up statistical	Bottom-up building physics
Benefits	- Focus on the interaction between the energy sector and the economy at large. Capable of modelling the relationships between different economic variables an energy demand Avoid detailed technology descriptions. Able to model the impact of different social cost-benefit energy and emission policies and scenarios. Use aggregated economic data	- Include macroeconomic and socioeconomic effects. Able to determine a typical end-use energy consumption. Easier to develop and use. Do not required detailed data (only billing data and simple survey information)	- Describe current and prospective technologies in detail. Use physically measurable data. Enable policy to be more effectively targeted at consumption. Assess and quantify the impact of different combination of technologies on delivered energy. Estimate the leas-cost combination of technological measures to meet given demand
Limitations	- Depend on past energy economy interactions to project future trends. Lack the level of technological detail. Less suitable for examining technology-specific policies. Typically assume efficient markets, and no efficiency gaps	- Do not provide much data and flexibility. Have limited capacity to assess the impact of energy conservation measures. Rely on historical consumption data. Require large sample. Multicollinearity.	- Poorly describe market interactions. Neglect the relationships between energy use and macroeconomic activity. Require a large amount of technical data. Do not determine human behavior within the model but by external assumptions.

building energy regulations have led to suboptimal building energy design in many existing residential buildings in Jordan [21]. The lack of reliable data on the share of electrical energy consumption by end-use in residential buildings in Jordan makes it difficult to evaluate the effectiveness of energy-saving strategies [22]. Two major references presented data on housing stock in Jordan: The Department of Statistics (DOS) housing survey and Jordan Green Building Council (JGBC) Survey.

The DOS survey aimed to assess the state of housing in the country, including housing conditions, access to basic amenities, affordability, and housing preferences [23]. The JGBC survey addressed the building characteristics and energy performance of Apartments in Amman [16]. A recent study combined the available housing surveys highlighting the detailed characteristics and structure of JGBC and DOS surveys [24].

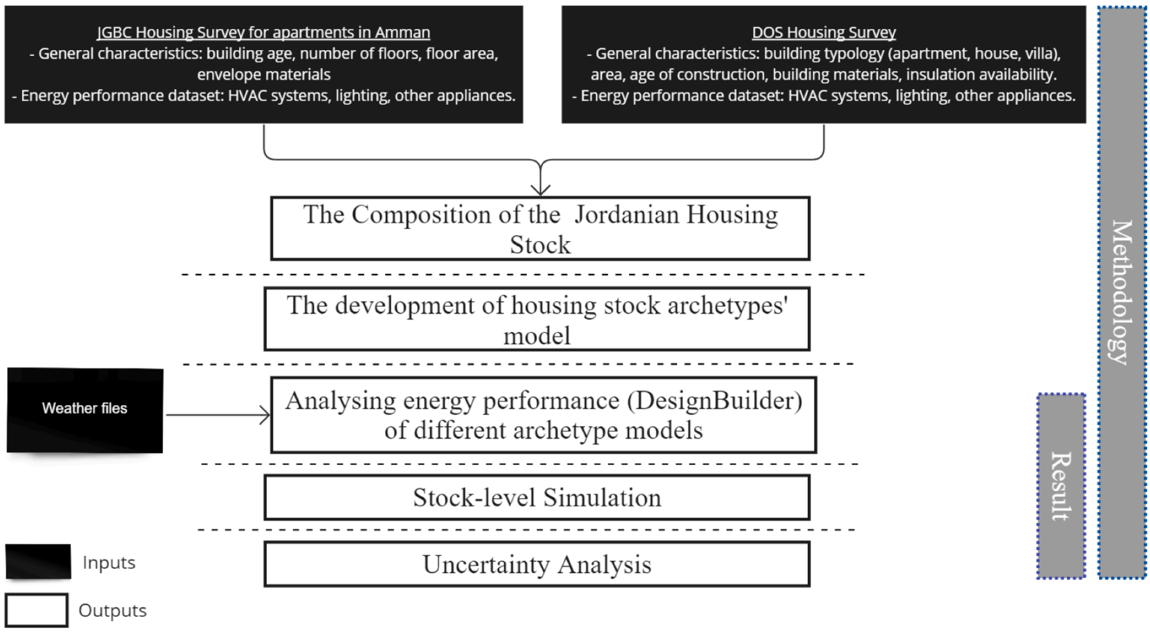


Fig. 2. The structure of the modelling method for JHEM.

2.2. *Stock modelling approaches*

Housing stock models are useful tools in evaluating the energy performance of residential buildings [25]. The top-down and bottom-up approaches, which are used to predict energy consumption and their associated carbon emissions, are defined by the International Energy Agency (IEA) as two major categories of modelling techniques [26]. Both methodologies exhibit inherent strengths and weaknesses, with the choice of approach contingent upon the specific research question and the availability of data. Table 2 highlights the benefits and limitations of bottom-up statistical and building physics, and top-down modelling approaches.

2.2.1. *Top-down stock modelling approach*

The top-down method operates at an aggregated level and is intended to match a historical time series of data on national energy consumption or carbon emissions. It can be categorized as econometric and technological top-down models, which are used to examine the interactions between the energy industry and the economy at large [25,27]. According to a study by Hong et al. (2017), the top-down approach is more suitable for estimating energy consumption at a national level and identifying broad trends in energy use [28]. The study found that the top-down approach was effective in estimating energy consumption in residential buildings in South Korea based on census data.

2.2.2. *Bottom-up stock modelling approach*

According to a study by Du et al. (2018), the bottom-up approach is more suitable than top-down approach for detailed analysis of energy consumption patterns and identifying specific areas where improvements can be made [29].

The bottom-up method, which operates at a disaggregated level, requires large empirical database to describe each individual building fabric and system component effectively [30]. Statistical and building physics-based methods are two independent bottom-up methodologies, both can be used to calculate the energy consumption of specified end-uses, depending on the type of data input and data format [31].

Bottom-up building physics-based stock models require data input composed of quantitative data on physically measurable variables, such as space heating and cooling systems, building elements; walls, roof, floor, windows, and doors, along with their thermal characteristics (e.g., U-values), ventilation rates, the energy consumption of appliances, number of occupants, external temperature, etc. [32].

Three major approaches based on the building physics-based method have evolved, which are:

- Distribution: This approach involves a detailed examination of individual buildings or components within a building to calculate energy usage and evaluate the impact of various policies or strategies on energy efficiency [33].
- Archetype: classification of the housing stock based on the data available from a large number of individual buildings.
- Sample: is based on actual sample dwelling data, the technique estimates regional or national energy consumption and carbon emissions [25].

Energy efficiency measures derived from a stock model could inform policies to mitigate the challenge of increasing primary energy sources to meet the demands in Jordan. The residential sector plays a key role in this challenge which makes Net-Zero Energy Buildings gain higher interest as a crucial solution.

In Saudi Arabia, another country in the Middle East, a study by Krarti, Aldubyan & Williams, 2020 [34] conducted the engineering bottom-up approach to develop a housing stock model using deterministic engineering analysis of representative building prototypes. Raslan & Mavrogianni, 2013 [27] developed a housing stock model for Egypt using a physics-based, bottom-up, approach. Studies in other countries have used bottom-up method using various methodological approaches. For example, in the UK, five models have been compared describing the key characteristics of each model [25]. On the other hand, the top-down method - which relies on historical data sets and is used in macroeconomic analysis, has also been used in the UK to develop a housing stock model [25].

3. Methodology

3.1. *Generating Jordan housing energy model (JHEM)*

A physics-based bottom-up building stock analysis, the archetypes approach, is applied to generate Jordanian housing stock models. A

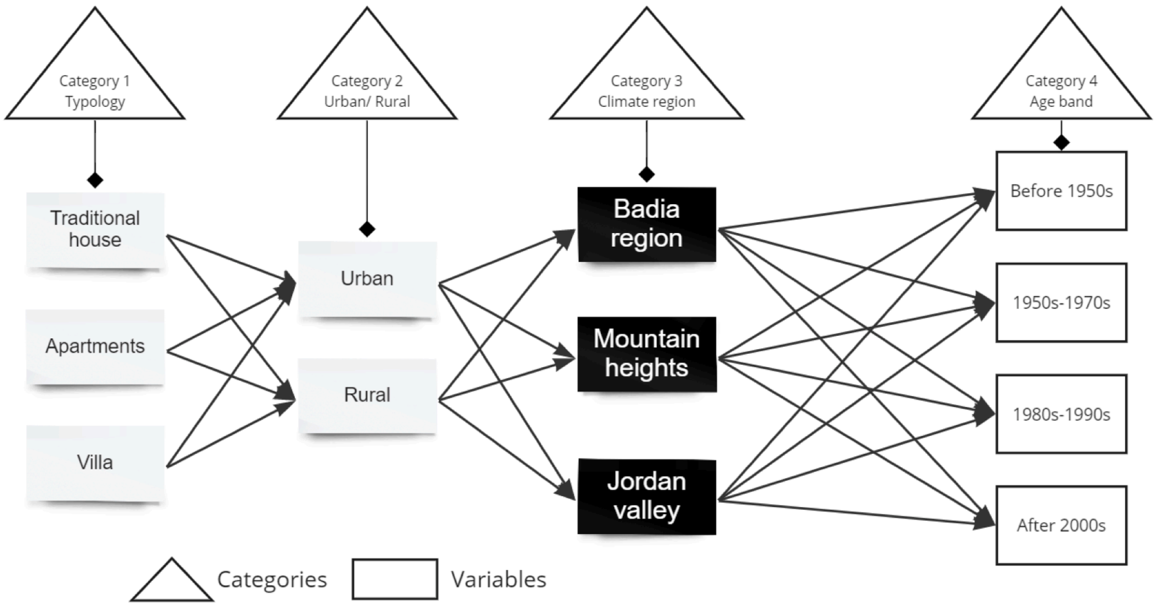


Fig. 3. Flow-chart of the investigation of the current Jordanian housing stock.

Table 3
The distribution of cities of Jordan into country climatic regions.

Climatic Regions	Cities in Jordan
Desert	Ma'an, Mafraq
Mountain	Amman, Zarqa, Irbid, Balqa', Madaba, Ajloun, Jerash, Karak
Jordan Valley	Valley from the sea of Galilee to the dead sea, Wadi Araba, Aqaba

database is developed based on data collected under the JGBC survey and the DOS housing survey, supplemented with parameters on building characteristics from other national sources and the building code.

Data-driven approach and hybrid simulation method are emerging and promising techniques for building archetype analysis, especially at the urban scale. Data-driven approach uses statistical and machine learning methods to analyze large and heterogeneous datasets of building energy consumption and performance, and to identify the key patterns and clusters of the building stock [35]. Data-driven approach can reduce the computational cost and the uncertainty of the simulation results, but it also requires large and reliable datasets, which are not always available or accessible [36]. Further, Hybrid simulation method combines the strengths of both data-driven and simulation-based approaches, by using data-driven methods to generate or refine the input data and parameters for the simulation models, or by using simulation models to supplement or validate the data-driven results [37]. Hybrid simulation method can improve the accuracy and robustness of the building archetype analysis, but it also introduces additional complexity and challenges in the model development and validation [36].

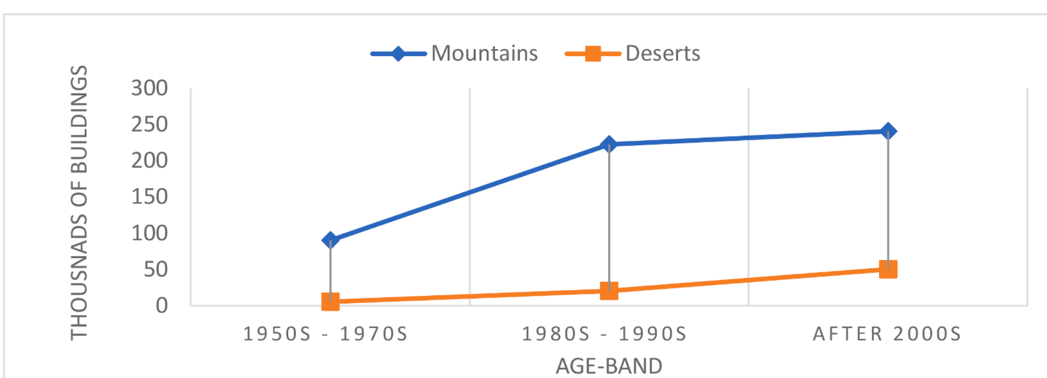


Fig. 4. Distribution of dwellings from 1950 to 2015 in Mountain and Desert climate regions in Jordan [23].

Table 4
Evaluated metrics for the Jordanian housing stock, elaborated from [24].

Typologies	Urban/ Rural	Metric 1Number of Buildings	% buildings	Metric 2Number of Units	% Units	Metric 3 Total Area (m2)	% Area
Apartment	Urban	272,169	38.7 %	1,236,578	61.4 %	191,361,900	73.9 %
	Rural	15,975	2.3 %	39,424	2.0 %	15,041,972	5.8 %
House	Urban	297,668	42.3 %	560,450	27.8 %	32,540,056	12.6 %
	Rural	101,135	14.4 %	171,544	8.5 %	17,608,476	6.8 %
Villa	Urban	15,449	2.2 %	5,339	0.3 %	2,109,150	0.8 %
	Rural	1,774	0.3 %	1,754	0.1 %	177,200	0.1 %
	Total	704,170	100 %	2,015,089	100 %	258,838,754	100 %

Table 5
Evaluated metrics for the Jordanian housing typologies (Apartment, House, Villa).

Typologies	Urban/ Rural	Climate region	Buildings	% buildings	Units	% Units	Area - Units	% Area	Age-band
Apartment	Urban	Mountains	253,350	36.0%	1,167,481	57.9%	178,381,175	68.9%	1950s-1970s 1980s-1990s After 2000s
		Desert	13,340	1.9%	62,713	3.1%	10,121,600	3.9%	1950s-1970s 1980s-1990s After 2000s
		Jordan valley	5,479	0.8%	6,384	0.3%	2,859,125	1.1%	
	Rural	Mountains	9,913	1.4%	31,807	1.6%	11,047,300	4.3%	1950s-1970s 1980s-1990s After 2000s
		Desert	4,616	0.7%	5,285	0.3%	3,007,825	1.2%	
		Jordan Valley	1,446	0.2%	2,332	0.1%	986,847	0.4%	
House	Urban	Mountains	263,209	37.4%	481,230	23.9%	26,570,353	10.3%	1950s-1970s 1980s-1990s After 2000s
		Desert	33,389	4.7%	77,986	3.9%	5,484,000	2.1%	1950s-1970s 1980s-1990s After 2000s
		Jordan Valley	1,070	0.2%	1,234	0.1%	485,703	0.2%	
	Rural	Mountains	71,965	10.2%	115,962	5.8%	10,827,625	4.2%	1950s-1970s 1980s-1990s After 2000s
		Desert	28,140	4.0%	54,652	2.7%	6,489,350	2.5%	1950s-1970s 1980s-1990s After 2000s
		Jordan Valley	1,030	0.1%	930	0.0%	291,501	0.1%	
Villa	Urban	Mountains	15,045	2.1%	4,945	0.2%	2,045,800	0.8%	
		Desert	404	0.1%	394	0.0%	63,350	0.0%	
		Jordan Valley	0	0.0%	0	0.0%		0.0%	
	Rural	Mountains	1,581	0.2%	1,571	0.1%	142,800	0.1%	
		Desert	193	0.0%	183	0.0%	34,400	0.0%	
		Jordan Valley	0	0.0%	0	0.0%	0	0.0%	
Total			704,170		2,015,089		258,838,754		
Total Percentage				83.6%		87.6%		83.4%	
				86.9%		92.3%		91.5%	
				95.6%		98.8%		96.2%	

The models in this study are developed using the simulation-based approach using DesignBuilder [38]– an interface software for EnergyPlus, which allows for detailed modelling of building components and systems. The generation of energy models follows a three-level approach; starting with understanding the state of existing housing stock and the available data on dwellings in Jordan, followed by the categorization of data, and finally, the development of housing archetypes that represent the entire stock. This model will be used for analysing the energy performance of the stock through the simulation of different archetype models. Finally, uncertainty analysis is conducted accounting for variation in input data to obtain reliable ranges for energy performance. Fig. 2 represents the structure of the methodology developed for generating JHEM and the simulation of energy use of the residential stock.

3.1.1. The composition of the Jordanian housing stock

Understanding existing housing stock is the first step in evaluating the energy performance and the potential for energy efficiency improvements. Two housing surveys that can help characterize Jordan's housing stock are those conducted by the JGBC and the DOS. DOS housing survey was carried out to compile a thorough database of Jordan's domestic energy usage. In order to develop a benchmark, the JGBC conducted a survey in Amman to determine the energy consumption of residential apartments after the 2000 s. Both surveys contained valuable data about the Jordanian housing stock, but they have still not been used for generating a national housing stock model.

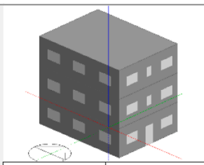
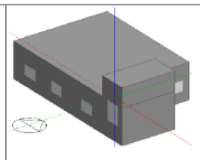
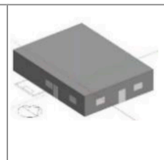
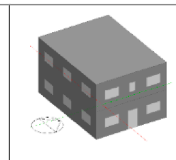
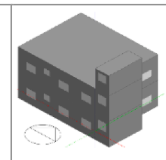
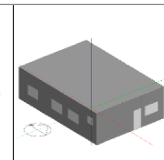
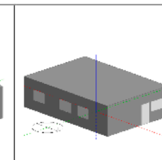
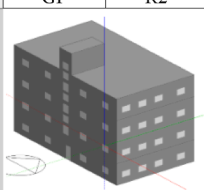
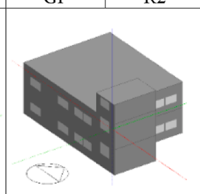
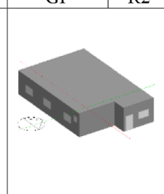
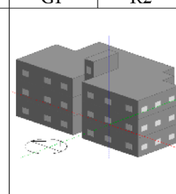
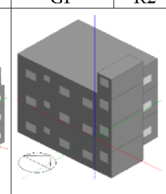
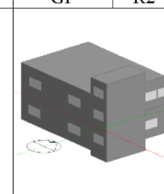
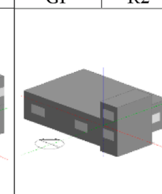
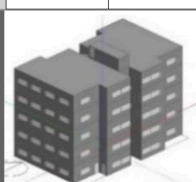
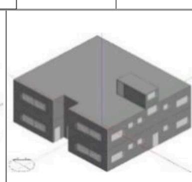
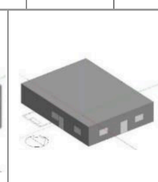
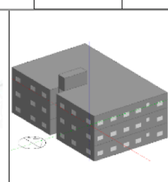
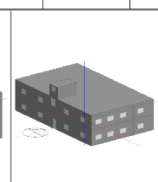
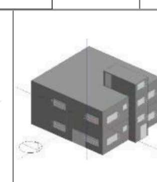
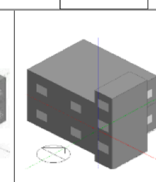
In a recent paper [24], the study produced an integrated dataset of the national dwellings' characteristics. This integrated dataset is used in this study to generate a housing stock model in Jordan.

3.1.2. Housing stock data categorization

The classification used to identify archetypes, as shown in Fig. 3, is based on the typology, urban/rural distribution and age band based on the analysis of a housing survey database of Jordanian dwellings issued by the DOS [23]. The dwellings are classified into three main typologies that represent the Jordanian housing stock: Traditional house, Apartment and Villa. Classification of Jordan's cities according to climate zones is a criterion used to identify the archetypes. Cities in Jordan are distributed into three climatic regions, as shown in Table 3.

The majority of buildings used in Jordan Valley region are commercial units (hotels) [39], excluding Aqaba city. Within each climate region and typology, the buildings are divided into age groups according to when they were built; before 1950, between 1950 and 1970, between 1980 and 1990, and after 2000. This age-band categorisation followed the characteristics of dwellings in Jordan based on the DOS data. The residential buildings' distribution in Mountain, Jordan Valley, and Desert regions for the age-band from 1950 to 2015 is presented in Fig. 4. The number of dwellings in Jordan Valley region represents less than 1 % of the total share of residential buildings in Jordan.

Table 6
Renderings of Energy Model for 21 archetypes; Houses and apartments within the three age-bands.

	AUM		HUM		HRM		AUD		ARM		HUD		HRD	
	Apartment-Urban-Mountain		House-Urban-Mountain		House-Rural-Mountain		Apartment-Urban-Desert		Apartment-Rural-Mountain		House-Urban-Desert		House-Rural-Desert	
1950s-1970s														
	75 m²	W3	125 m²	W3	125 m²	W4	125 m²	W4	125 m²	W4	75 m²	W3	75 m²	W4
	GF	R2	GF	R2	GF	R2	GF	R2	GF	R2	GF	R2	GF	R2
1980s-1990s														
	175 m²	W2	175 m²	W2, 3	125 m²	W3	125 m²	W3	125 m²	W4	125 m²	W2,3	125 m²	W3
	GF	R1	GF	R1	GF	R2	GF	R2	GF	R2	GF	R1	GF	R2
2000s														
	175 m²	W1	175 m²	W1	175 m²	W2	175 m²	W2,3	175 m²	W3	175 m²	W1	175 m²	W3
	GF	R1	GF	R1	GF	R2	GF	R1	GF	R2	GF	R1	GF	R2

W: Wall, GF: Ground Floor, R: Roof,

3.1.3. *The definition of housing stock energy models*

According to the DOS data [23], the Jordanian residential building stock was categorised by three metrics: number of buildings, number of units and area of housing units, within urban and rural zones. Table 4 [24] shows that the majority of housing units are concentrated in urban areas. The table outlines the metrics used for determining the archetypes within each typology after employing the classification approach. Based on a preliminary analysis of the available databases, the stock can be disaggregated into several archetypes that are characterized by age, number of floors, unit floor area and other characteristics.

The different archetypes are classified into twenty-one variants. The number of buildings (M1), the number of units (M2), and the area of units (M3) are the parameters used to determine the archetypes from the entire housing stock of each building typology within different climate regions and age-band. The percentages of buildings, units and areas illustrated in Table 4 correspond to the proportion from the entire housing stock. The archetypes that fall within 1 % or less, in terms of the percentage in one of the three parameters of the total number of buildings, number of units, and areas are excluded. Following that, the villa archetypes have been excluded. This is a stricter criterion than, for example, Buckley et al. (2021) who developed an Urban Building Energy Model (UBEM) for Dublin, Ireland, based on 12 archetype buildings that represent 80 % of the floor area [40].

The provided local sources in Jordan, including local building codes, material manufacturers, and research articles [16,41], contain valuable information related to building envelope materials and characteristics. For example, Energy Efficient Building Code (EEBC) for Jordan, was prepared utilizing local, regional, and international resources, considering architectural aspects, mechanical considerations, and electrical principles [42]. These sources could be a valuable reference for defining the information on building envelope materials and their properties through compiling existing data.

3.2. *Uncertainty analysis*

When conducting energy-building performance simulations, accounting for uncertainties in input data is crucial for obtaining reliable results. This uncertainty in the inputs imposes a limit on our confidence in the output of the energy model. Such errors are quantified in uncertainty analysis which treats the simulation output as "probabilistic" rather than "deterministic" [51].

Deterministic and probabilistic uncertainty analysis are essential approaches in evaluating energy models. Deterministic methods typically rely on fixed parameters and inputs, providing a single, best-estimate outcome. These approaches are useful for assessing energy systems under known conditions but may overlook the impact of uncertainties [43]. On the other hand, probabilistic methods account for uncertainty by considering a range of possible scenarios and associated probabilities. This approach is particularly valuable when dealing with complex energy systems subject to various sources of variability, such as renewable energy generation or demand fluctuations [44]. Both deterministic and probabilistic approaches play crucial roles in understanding and managing energy model uncertainties, with probabilistic methods offering a more comprehensive view of the system's behaviour under uncertain conditions [45].

Probabilistic analysis involves an assessment of the model across a range of parameter values, making decisions based on the resulting distribution of outputs. In contrast, deterministic analysis focuses on evaluating the model using the mean values of the parameters, providing a singular output for decision-making purposes.

One factor at a time (OFAT) analysis is a method of designing experiments that involves testing the effect of one input variable on the output variable, while keeping all other input variables constant [46]. This method is simple and intuitive, but it has several disadvantages compared to other methods that test multiple input variables

Table 7
The characteristics of building envelope materials used for constructing housing stock in Jordan.

Exterior wall	Materials	Thickness (mm)	U-Value (W/m^2. k)
W1	Cut stone	60	1.99
	Cast in-site concrete	80	
	Air gap	50	
	Hollow concrete	100	
	Cement plastering	20	
W2	Cut stone	60	2.55
	Cast in-site concrete	80	
	Hollow concrete	100	
	Cement plastering	20	
W3	Cement plastering	20	1.27
	Hollow concrete	100	
	Air gap	50	
	Hollow concrete	100	
	Cement plastering	20	
W4	Hollow concrete	100	1.71
	Air gap	50	
	Hollow concrete	100	
	Cement plastering	20	
Floor		Thickness (mm)	U-Value (W/m^2. k)
GF	Ceramic tiling	8	0.94
	Cement Mortar	20	
	Gravel and sand	70	
	Waterproofing Bitumen roll	4	
	Lightweight concrete	100	
	Reinforced concrete	100	
	Gravel and sand	70	
	Cement plastering	10	
Roof		Thickness (mm)	U-Value (W/m^2. k)
R1	Terrazzo tile	0.025	1.63
	Cement Mortar	20	
	Gravel and sand	70	
	Waterproofing Bitumen roll	4	
	Lightweight concrete	100	
	Reinforced concrete	300	
	Cement plastering	20	
R2	Cement Mortar	20	2.36
	Waterproofing Bitumen roll	4	
	Lightweight concrete	100	
	Reinforced concrete	300	
	Cement plastering	20	

simultaneously, such as Monte Carlo uncertainty analysis [47].

The Monte Carlo method has proven to be a robust and versatile approach in assessing uncertainty and variability in various domains. For example, the context of thermal comfort indices such as Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD), researchers have employed the Monte Carlo method to enhance the accuracy and reliability of assessments [48].

One notable application involves a study on thermal comfort indices where the Monte Carlo method was utilized to assess the uncertainty of PMV and PPD. This study emphasized the benefits of employing a measuring set with an operative temperature probe in enhancing the precision of thermal comfort evaluations [48,49].

Furthermore, Prataviera et al. [50] applied Monte Carlo sensitivity and uncertainty analysis to an urban building energy model to evaluate the impact of input uncertainty on urban building energy simulations. Another study used Monte Carlo simulation to evaluate the uncertainty associated to the use of a simplified model for the estimation of the energy consumption of a given building [51].

Following this, this study delves into probabilistic simulations employing the Monte Carlo method. Monte Carlo analysis is a computational technique used for probabilistic modelling and simulation. It relies on repeated random sampling to obtain numerical results, making it suitable for situations involving uncertainty and variability. This method is widely employed in various fields, including engineering, finance, and statistics, to predict outcomes and assess the impact of different parameters on a system or model [52 53].

By doing so, this study can thoroughly evaluate the effects of uncertainty in input data on the outcomes of energy models. This rigorous analysis not only enhances the robustness of findings but also offers valuable insights into the reliability of energy-related decisions and policies.

4. Results

4.1. The development of housing stock archetypes' models

4.1.1. Defining archetypes characteristics

The dwellings that represent the highest percentages, based on the three metrics (M1, M2 and M3), are identified in Table 4; Apartment-Urban-Mountain (AUM), House-Urban-Mountain (HUM) and House-Rural-Mountain (HRM) with total '*83.6 %, 87.6 %, and 83.4 %*' regarding M1, M2, and M3 respectively. These are followed by Apartment-Urban-Desert (AUD), Apartment-Rural-Mountain (ARM), House-Urban-Desert (HUD), and House-Rural-Desert (HRD), which together make up a total of *95.6 %* of its overall number of buildings, *98.8 %* of the stock's total number of residential units, and *96.2 %* respective areas.

Each of these 7 categories is divided into 3 age-bands; from the 1950 s to 1970 s, 1980 s to 1990 s, and the after 2000 s dwellings, to count 21 models representing the entire housing stock as shown in Table 5.

The characteristics of energy models for Apartments 'AUM, AUD, ARM' and Houses 'HUM, HUD, HRM, and HRD' are defined using the available data from the DOS housing survey and JGBC survey. The detailed characteristics within different age-band and climate regions of the energy systems are illustrated in the integrated dataset generated previously [24]. Rendering of the 21 energy models for the archetypes is illustrated in Table 6 using DesignBuilder including the envelope characteristics followed in Table 7. The type of building materials, U-values, and thickness are identified in Table 7 to provide a comprehensive overview of building envelope components used in construction.

As presented in Table 5 and Table 6, the buildings are categorized as apartments and traditional houses based on the percentage classification of the housing census in Jordan (the Villa Archetype had been excluded due to low number of buildings which did not pass the above mentioned threshold). The required data for generating the models of the most prevalent archetypes (After 2000 s AUM, HUM, and HRM) is defined in Table 8. The archetypes models are defined based on the prevalence of the primary parameters that define the envelope characteristics and building physics using the same data sources. It is worth highlighting that the operating schedule of energy models remains fixed, and this is due to the absence of information regarding models that are not fully utilized throughout the year.

4.1.2. Analysis of energy consumption of Jordan housing stock

A dynamic simulation approach using DesignBuilder is adopted to estimate the annual energy use of the housing stock through the analysis of House archetypes (HUM, HRM, HUD, and HRD) and Apartments (AUM, ARM, and AUD). The climate weather files provided by the JGBC for the various climate regions in 2021 are used for energy analysis [60]. The average temperature varies depending on the climate region. For instance, the average temperature in Amman ranges from 5̊C to 30̊C throughout the year, while Aqaba in Jordan valley region has a warmer climate temperatures ranging from 15̊C to 40̊C, and in desert region, the temperature ranges from 11̊C to 36̊C with a 16.2 kph average wind speed [61]. The average wind speed in Amman and Aqapa varies from 11.2 to 13.7 kph, and 12.1 to 15.6 kph respectively [61]. The distribution of archetypes within the three age bands; *1950 s-1970 s, 1980 s-1990 s, and after 2000 s,* is numbered 1, 2 and 3 sequentially in Fig. 5,

Table 8
The characteristics of the most prevalent residential buildings in Jordan; AUM, HUM, and HRM past 2000s. (See above-mentioned references for further information.)

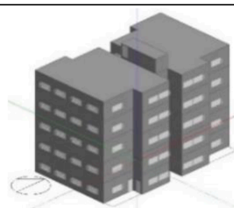
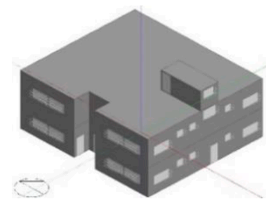
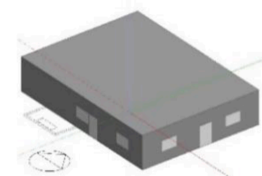
		AUM 2000s	HUM 2000s	HRM 2000s	Source
General	Number of floors	5	2	1	[23]
	Units/floor	2	1	1	[23]
	Area/ Unit	175 m²	250 m²	175 m²	[23]
	Plan				*Assumption*
	3D mode				*Assumption*
Fabric	External wall U-Value	1.99 w/m²K	1.99 w/m²K	2.55 W/m²k	[54] , [23]
	Slab between floors U-Value	1.7 W/m²k	1.7 W/m²k	1.7 W/m²k	[54]
	Infiltration	0.6 ach	0.6 ach	0.85 ach	[55]
	Door U-value	2.85 W/m²k	2.85 W/m²k	2.85 W/m²k	[2]
Activity	Operation schedule	Weekday Hours / Factor 5:00am – 7:00 am / 0.75 7:00am - 2:00 pm / 0.25 2:00pm - 5:00 am / 1 Weekend Hours / Factor 11:00am – 1:00 pm / 0.50 1:00pm - 11:00 pm / 1	Weekday Hours / Factor 5:00am – 7:00 am / 0.75 7:00am - 2:00 pm / 0.25 2:00pm - 5:00 am / 1 Weekend Hours / Factor 11:00am – 1:00 pm / 0.50 1:00pm - 11:00 pm / 1	Weekday Hours / Factor 5:00am – 7:00 am / 0.75 7:00am - 2:00 pm / 0.25 2:00pm - 5:00 am / 1 Weekend Hours / Factor 11:00am – 1:00 pm / 0.50 1:00pm - 11:00 pm / 1	[54]
	Occupancy (m²/person/unit)	35	40	35	[55]
	Catering	LPG -190 Kg/Y – 15 Cylinder/Year	LPG -225 Kg/Y – 18 Cylinder/Year	LPG -190 Kg/Y – 15 Cylinder/Year	*Assumption,* [16]
Openings	Glazing type	Double clear glass - 6mm 13 mm Air	Double clear glass - 6mm 13 mm Air	Single clear glass 6mm	[55], [16]
	Dimensions	Width 2.00 Height 1.00	Width 2.00 Height 1.00	Width 1.50 Height 1.00	[16]
	Frame	Aluminum 0.04	Aluminum 0.04	Aluminum 0.04	[16]
	Solar transmission SHGC	0.53	0.53	0.71	[16]
	WWR	35%	40%	30%	[16]
	Glazing U-Value W/m². k	2.65	2.65	5.20	[16]
	Reveal (m)	0.2	0.2	0.2	[16]
Lighting	Lighting intensity level Lux	Bedrooms, Stairs 100 Living room, Bathroom 150 Kitchen 225	Bedrooms, Stairs 100 Living room, Bathroom 150 Kitchen 225	Bedrooms, Stairs 100 Living room, Bathroom 150 Kitchen 225	Assumption, [56]
HVAC	Ventilation (ach)	Summer: 0.6 ach Winter: 0.6 ach	Summer: 0.6 ach Winter: 0.6 ach	Summer: 5 ach Winter: 0.85 ach	Assumption, [57]
	Heating	Electric heater (1)	Electric heater (1)	Gas heater LPG (0.70)	[55], [23]
	Cooling	Air conditioner (AC Split unit CoP 2.4)	Air conditioner (AC Split unit CoP 2.4)	Electric fans	[58]
	Fan power density w/m²	-	-	2.3 (100 W- 4 box fans)	Typical product
	DHW source/CoP	Electricity - 0.9	Electricity - 0.9	Electricity – 0.9	Assumption [59]
	Daily DHW demand (l/P)	50	50	50	DB default data for dwellings

Fig. 6 and Table 9. The breakdown of annual energy consumption is presented in Fig. 5, following the classification used for benchmarking new apartments in Amman for energy analysis by the JGBC.

Heating, cooling, lighting, domestic hot water (DHW), electrical appliances, and energy consumed for cooking are considered.

One approach to assess the validity of energy models is by comparing them to local energy consumption data. Local housing energy consumption data provides real-world insights into energy usage patterns,

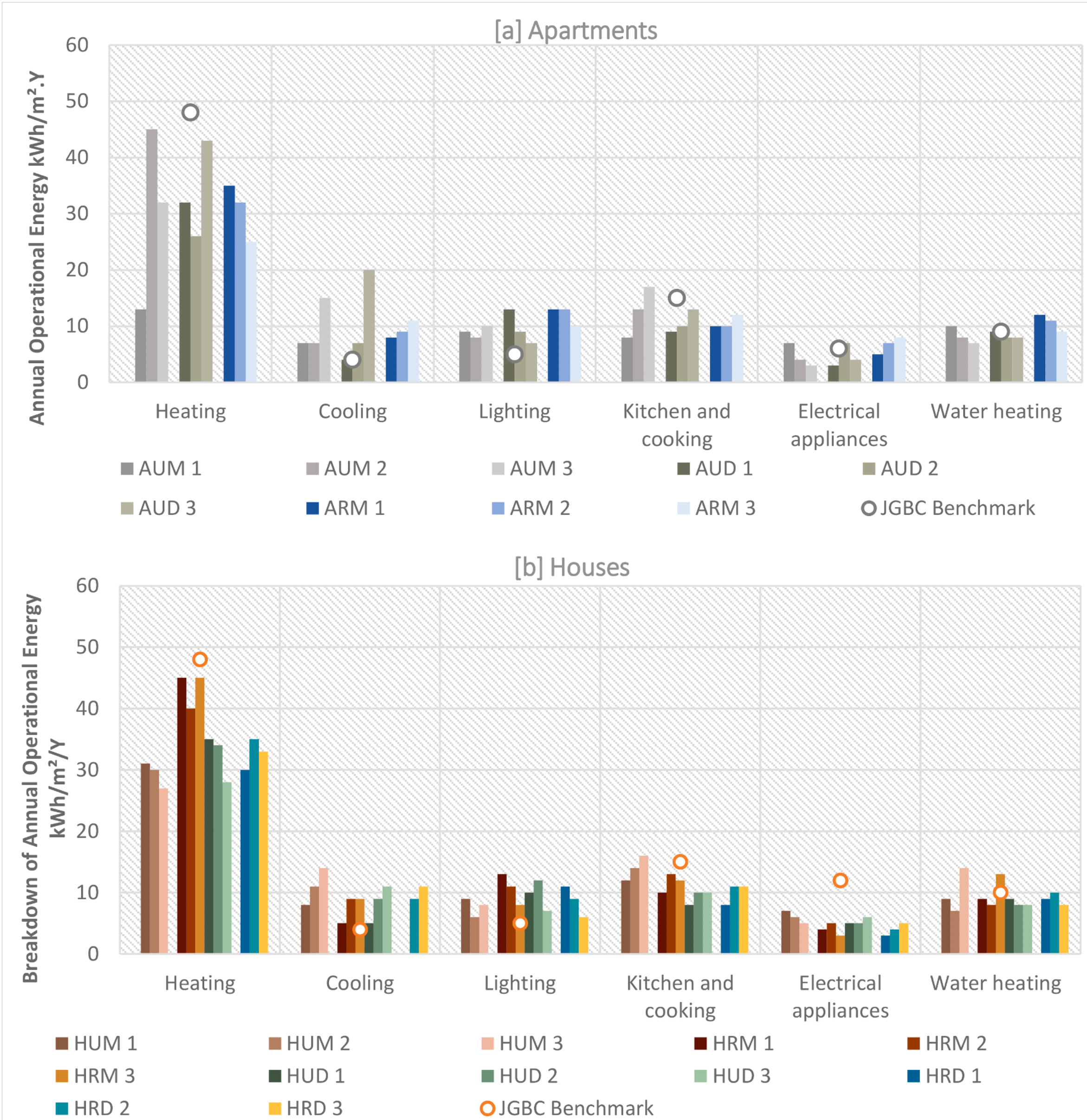


Fig. 5. The analysis of annual energy use of the residential archetypes in comparison to a local JGBC benchmark for [a] apartments and [b] houses - (1:1950 s-1970 s, 2:1980 s-1990 s, 3: after 2000 s).

helping to refine and improve the accuracy of energy models. As such, the combination of energy models and local consumption data serves as a potent tool for evidence-based energy policy formulation and implementation.

Fig. 6 presents the annual energy use (kWh/m^2 per annum) of housing archetypes in Jordan. The energy consumption of housing stock in Jordan is estimated using the energy use multiplied by the total area of each housing archetype as shown in Table 9.

The total energy use of housing stock using energy models equals 19,523 GWh. However, according to the Ministry of Energy and Mineral Resources (MEMR) 2021 Energy Database, housing stock in Jordan accounts for 1,549 thousand toe (18,014. 87 GWh) of the total share of the energy mix in Jordan [62]. The estimated annual energy is approximately 8.3 % higher than the energy consumption of the entire housing stock in Jordan based on the local database.

4.2. Uncertainty analysis (UA)

This study seeks the uncertainty analysis of key input variables affecting energy analysis of housing stock models in Jordan. The variables encompass construction quality (infiltration, U-values for external envelope ‘wall, floor, roof and glazing’), building technical systems (heating system efficiency, cooling system efficiency, lighting normalized power density, and miscellaneous power density), and Occupant behavior (number of occupants, internal temperature set-point). Table 10 sets out the standard deviations and distribution types for the housing stock archetypes models following the BS EN 15603:2008 standard [63] and using default data at DesignBuilder uncertainty analysis module [64]. The uncertainty analysis is obtained for the 21 models of archetypes that represent the entire housing stock in Jordan.

A Monte Carlo analysis was performed using random sampling (a sample of 200 runs for each archetype model). This involves repeated running of the model with different values for the uncertain parameters in each simulation run drawn randomly from the defined uncertainty

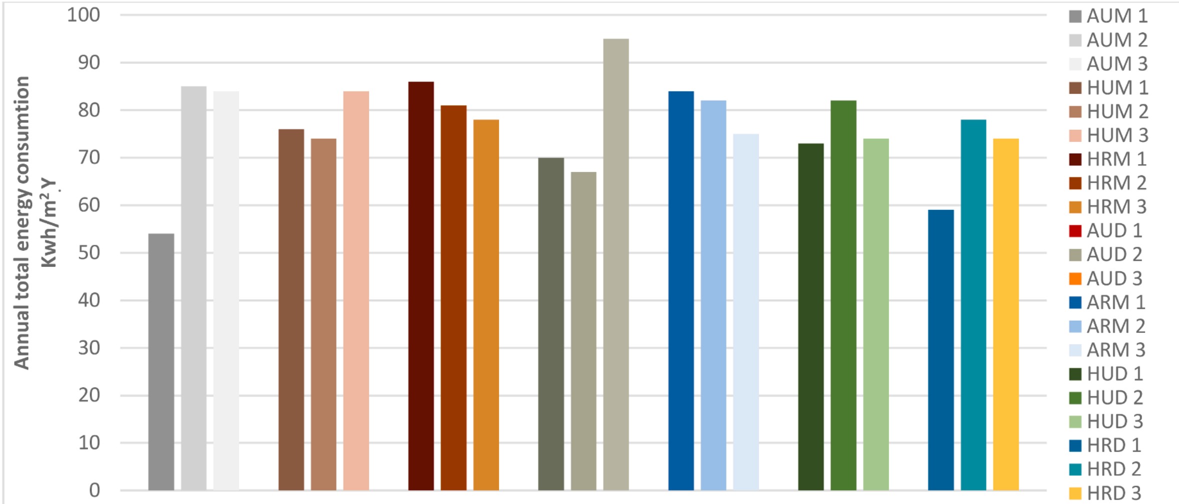
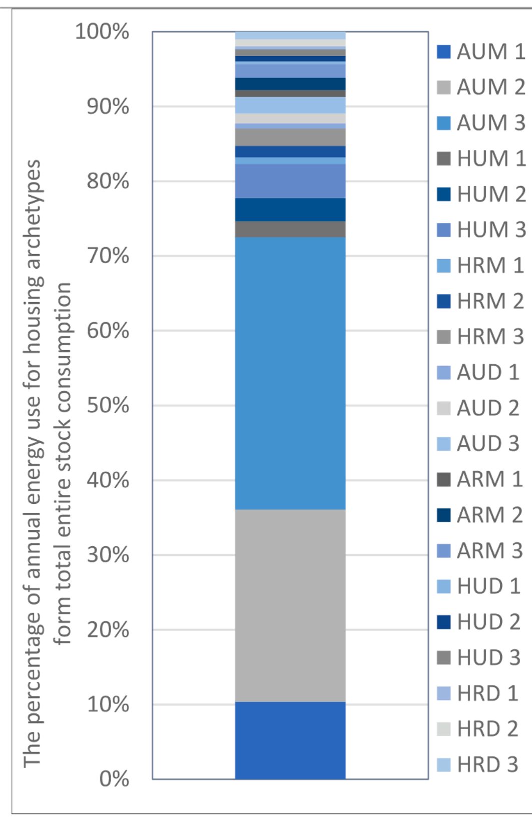


Fig. 6. The annual operational energy use of the residential archetypes in Jordan (1:1950 s-1970 s, 2:1980 s-1990 s, 3: after 2000 s).

Table 9
The analysis of annual energy use for building archetypes within the housing entire stock.

Archetype	EUI kWh.m²/Y	Area/Unit m²	Total Area m²	Annual GWh
AUM1	54	75	35,676,235	1,927
AUM2	85	175	62,433,411	5,307
AUM3	84	175	80,271,529	6,743
HUM1	76	125	5,314,070	404
HUM2	74	175	9,299,623	688
HUM3	84	250	11,956,658	1004
HRM1	86	125	2,165,525	186
HRM2	81	125	3,789,668	317
HRM3	78	175	4,872,431	373
AUD1	70	75	2,024,320	142
AUD2	67	125	3,542,560	237
AUD3	95	125	4,554,720	433
ARM1	84	125	2,209,460	186
ARM2	82	125	3,866,555	317
ARM3	75	175	4,971,285	373
HUD1	73	75	1,096,800	80
HUD2	82	125	1,919,400	157
HUD3	74	125	2,467,800	183
HRD1	59	75	1,297,870	77
HRD2	78	125	2,271,272	177
HRD3	74	175	2,920,207	216
Total				19,523



EUI: Energy Use Intensity. (1:1950 s-1970 s, 2:1980 s-1990 s, 3: after 2000 s).

distributions. The output of one run is a single estimate of total energy, so the output from multiple runs is a distribution of modelled total energy in each archetype.

Fig. 7 shows the outputs for total energy consumption. Table 11 illustrates a comparison between a final energy consumption (kWh) projected by the model before the uncertainty analysis (Baseline), and the mean value of the uncertainty analysis that represents the average value derived from the uncertainty analysis in kWh for each of 21 archetypes' models.

Utilizing the outcomes derived from UA through the DesignBuilder tool for individual archetypes, including the mean, minimum, maximum, and Standard Deviation (SD), and taking into account the total area as detailed in 'Table 9' for diverse archetypes, this study assesses the uncertainty associated with energy consumption within the housing stock.

Fig. 8 represents a comparison between the total energy

Table 10
Standard deviations and distribution type for residential buildings.

	Variables	Mean/ Central estimate						Standard deviation	Distribution
		AUM1	AUM2	AUM3	HUM1	HUM2	HUM3		
Construction Quality	**Infiltration**	1	0.85	0.6	1	0.85	0.6	50 %	log-normal
	Thermal transmittance U-Value/ walls	1.27 W/m^2k	2.55 W/m^2k	1.99 W/m^2k	1.27 W/m^2k	2.55 W/m^2k	1.99 W/m^2k	10 %	Binomial
	Thermal transmittance U-Value/ Roof	2.36 W/m^2k	1.63 W/m^2k	1.63 W/m^2k	2.36 W/m^2k	1.63 W/m^2k	1.63 W/m^2k	10 %	Binomial
	Thermal transmittance U-Value/ Floor	0.94 W/m^2k	0.94 W/m^2k	0.94 W/m^2k	0.94 W/m^2k	0.94 W/m^2k	0.94 W/m^2k	10 %	Binomial
	Thermal transmittance U-Value/ Glazing	5.2 W/m^2k	2.65 W/m^2k	2.65 W/m^2k	5.2 W/m^2k	5.2 W/m^2k	2.65 W/m^2k	10 %	Binomial
Building Technical Systems	**Heating system efficiency**	0.65	0.70	1.00	0.70	1.00	0.85	5 %	log normal for x and 1-x
	Cooling system efficiency	–	–	2.4	–	2.4	2.4	5 %	log normal for x and 1-x
	Lighting normalized power density (W/m2-100 lx)	1.85	1.29	1.29	1.85	1.29	1.29	10 %	log-normal
	Miscellaneous power density (W/m2)	4	4	5	4	4	4	10 %	log-normal
Occupant Behavior	**Internal temperature**	21 ℃	21 ℃	21 ℃	21 ℃	21 ℃	21 ℃	1 ℃	Normal distribution
	Number of occupants	4	5	5	4	5	6	10 %	log-normal
		Mean/ Central estimate						Standard deviation	Distribution
	Variables	**HRM1**	**HRM2**	**HRM3**	**AUD1**	**AUD2**	**AUD3**		
Construction Quality	**Infiltration**	1	1	0.85	1	0.85	0.6	50 %	log-normal
	Thermal transmittance U-Value/ walls	1.71 W/m^2k	1.27 W/m^2k	2.55 W/m^2k	1.71 W/m^2k	1.27 W/m^2k	2.55 W/m^2k	10 %	Binomial
	Thermal transmittance U-Value/ Roof	2.36 W/m^2k	2.36 W/m^2k	1.63 W/m^2k	2.36 W/m^2k	1.63 W/m^2k	1.63 W/m^2k	10 %	Binomial
	Thermal transmittance U-Value/ Floor	0.94 W/m^2k	0.94 W/m^2k	0.94 W/m^2k	0.94 W/m^2k	0.94 W/m^2k	0.94 W/m^2k	10 %	Binomial
	Thermal transmittance U-Value/ Glazing	5.2 W/m^2k	5.2 W/m^2k	5.2 W/m^2k	5.2 W/m^2k	2.65 W/m^2k	2.65 W/m^2k	10 %	Binomial
Building Technical Systems	**Heating system efficiency**	0.65	0.70	0.70	0.70	0.70	0.65	5 %	log normal for x and 1-x
	Cooling system efficiency	–	–	–	–	–	2.40	5 %	log normal for x and 1-x
	Lighting normalized power density (W/m2-100 lx)	1.85	1.85	1.29	1.85	1.29	1.29	10 %	log-normal
	Miscellaneous power density (W/m2)	5	4	5	4	5	5	10 %	log-normal
Occupant Behavior	**Internal temperature**	21 ℃	21 ℃	21 ℃	21 ℃	21 ℃	21 ℃	1 ℃	Normal distribution
	Number of occupants	5	5	5	5	5	6	10 %	log-normal
		Mean/ Central estimate						Standard deviation	Distribution
	Variables	**ARM1**	**ARM2**	**ARM3**	**HRD1**	**HRD2**	**HRD3**		
Construction Quality	**Infiltration**	1	0.85	0.60	1	0.85	0.6	50 %	log-normal
	Thermal transmittance U-Value/ walls	1.71 W/m^2k	1.71 W/m^2k	1.27 W/m^2k	1.71 W/m^2k	1.27 W/m^2k	1.27 W/m^2k	10 %	Binomial
	Thermal transmittance U-Value/ Roof	2.36 W/m^2k	2.36 W/m^2k	1.63 W/m^2k	2.36 W/m^2k	2.36 W/m^2k	1.63 W/m^2k	10 %	Binomial
	Thermal transmittance U-Value/ Floor	0.94 W/m^2k	0.94 W/m^2k	0.94 W/m^2k	0.94 W/m^2k	0.94 W/m^2k	0.94 W/m^2k	10 %	Binomial
	Thermal transmittance U-Value/ Glazing	5.2 W/m^2k	5.2 W/m^2k	2.65 W/m^2k	5.2 W/m^2k	5.2 W/m^2k	2.65 W/m^2k	10 %	Binomial
Building Technical Systems	**Heating system efficiency**	0.70	0.70	0.70	0.70	0.70	0.65	5 %	log normal for x and 1-x
	Lighting normalized power density (W/m2-100 lx)	1.85	1.29	1.29	1.85	1.85	1.29	10 %	log-normal
	Miscellaneous power density (W/m2)	4	5	5	4	4	5	10 %	log-normal
Occupant Behavior	**Internal temperature**	21 ℃	21 ℃	21 ℃	21 ℃	21 ℃	21 ℃	1 ℃	Normal distribution
	Number of occupants	5	5	6	5	5	6	10 %	log-normal
		Mean/ Central estimate						Standard deviation	Distribution
	Variables	**HUD1**		**HUD2**		**HUD3**			
Construction Quality	**Infiltration**	1		0.85		0.60		50 %	log-normal
	Thermal transmittance U-Value/ walls	1.27 W/m^2k		2.55 W/m^2k		1.99 W/m^2k		10 %	Binomial
	Thermal transmittance U-Value/ Roof	2.36 W/m^2k		1.63 W/m^2k		1.63 W/m^2k		10 %	Binomial

(*continued on next page*)

Table 10 (*continued*)

	Variables	Mean/ Central estimate						Standard deviation	Distribution
		AUM1	AUM2	AUM3	HUM1	HUM2	HUM3		
	Thermal transmittance U-Value/ Floor	0.94 W/m^{2}k		0.94 W/m^{2}k		0.94 W/m^{2}k		10 %	Binomial
	Thermal transmittance U-Value/ Glazing	5.2 W/m^{2}k		5.2 W/m^{2}k		2.65 W/m^{2}k		10 %	Binomial
Building Technical Systems	**Heating system efficiency**	0.65		0.70		0.70		5 %	log normal for x and 1-x
	Cooling system efficiency	–		–		2.4		5 %	log normal for x and 1-x
	Internal temperature	21 ℃		21 ℃		21 ℃		1 ℃	Normal distribution
	Lighting normalized power density (W/m^2-100 lx)	1.85		1.29		1.29		10 %	log-normal
Occupant Behavior	**Number of occupants**	5		5		5		10 %	log-normal
	Miscellaneous power density (W/m^2)	4		5		5		10 %	log-normal

consumption of housing stock model in Jordan and the central estimation of uncertainty analysis. The energy consumption projected by the measured data (18,014.8 GWh) is higher than the mean value derived from the uncertainty analysis (16,132 GWh). Fig. 8 also shows that the measured data lies between the median (50th percentile) and the 75th percentile of the data derived from uncertainty analysis and, therefore, the discrepancy between total energy consumption derived from the housing stock model and the measured data can be explained by the expected variation in modelling input data.

At the same time, based on the uncertainty analysis, the 8.3 % discrepancy figured between the baseline and the measured data is less than the variation in most of these archetypes within a 95 % confidence interval. The analysis shows that the baseline results are well within the data under 2 SD from the mean in most archetypes models.

5. Discussion

5.1. Housing stock energy model/JHEM validation

According to the DOS, the number of housing units has grown significantly over the past decade. The data available on housing stock of Jordan, including housing surveys and statistics, determines the method used in this study for generating a housing stock model. Therefore, the selection of a method for generating a housing stock model depends on the data input locally available.

Despite excluding Villa typology, which represents less than 1 % of the stock as demonstrated in Table 4, when defining the entire stock, the total energy figure is around 8 % higher than the empirical data available for the housing stock in Jordan. This could be resulted of some modeling assumptions, such as the lack of information about buildings that are not fully utilized throughout the year, and the surrounding composition that provides shading on the building facades resulting a lower energy use. However, uncertainty analysis has demonstrated that the deviation in results falls within the data variability, typically remaining under 2 SD in all archetypes' models.

5.2. Key performance characteristics of dwellings

Fig. 5 presents a significant discrepancy between the energy consumption of housing archetypes models and the JGBC benchmark, specifically when comparing the benchmark with house archetypes models. The JGBC was conducted on apartments in Amman with 400 total number of respondents. It is noticeable that the total energy performance of apartment models is 1 % better than the benchmark of JGBC, and 6 % in terms of energy consumption for heating. It is worth mentioning here that AUM2 is the most representative archetype in terms of fabric and energy systems characteristics of buildings to the sample of JGBC housing survey. The AUM2 model represents the data pertaining to urban apartments in the mountain cities of Jordan, potentially accounting for the variation in outcomes compared to the JGBC sample in the city of Amman.

According to Table 4 and Table 5, apartments and houses in urban areas (AUM and HUM) could be a priority when defining the housing stock model and analysing the dwellings' total share of energy in Jordan, according to the high percentages in three metrics of area, number of units and number of buildings.

Table 7 presents the high U-values of the building envelope materials used in housing buildings in Jordan, highlighting the absence of thermal insulation utilization. Following the results of the total annual energy use of residential archetypes in Jordan in Fig. 6; AUD3, HUM3, and AUM3 archetypes presented the highest total annual energy use. At the same time, Table 9 indicates the AUM and HUM models as the more energy-intensive archetypes from the entire housing stock level, representing 83 % of the total energy consumption of dwellings in Jordan.

5.3. Applications of JHEM

The Minister of Mineral and Energy Resources (MEMR) in Jordan has categorized potential opportunities for enhancing energy efficiency within the building sector into three distinct classifications. These classifications encompass strategies pertaining to occupant behaviour, strategies associated with building design and the external envelope, and strategies linked to the equipment and systems responsible for energy consumption [65]. The studies in Jordan aimed at enhancing energy efficiency have primarily focused on the analysis of improvement strategies on specific case studies without considering the incorporation of holistic, comprehensive analysis for the entire housing stock. This study paves the way to understand the current and future energy performance of housing stock in Jordan.

The housing stock model developed in this study, JHEM, can be used by policymakers to improve the existing dwellings in terms of energy use and carbon intensity. Following the MEMR strategies; passive and active strategies are suggested to improve the energy performance of the entire housing stock. As shown in Table 7, the characteristics (U-Values) of building fabric components; walls, roofs, and windows, can be improved, as a passive strategy, to reduce the energy demand of dwellings. Examples include the use of glazing with lower U-values, such as double-glazing argon-filled windows, adding a wall thermal insulation, and roof insulation material with a tiling Construction layer.

For active strategies, while the heating system encounters the highest share of total energy consumption for each archetype, there is a potential to upgrade heating systems and move towards other fuel sources, such as the use of electric heat pumps. In terms of lighting energy use, the use of LED lighting systems in archetypes (1950 s-1970 s dwellings)

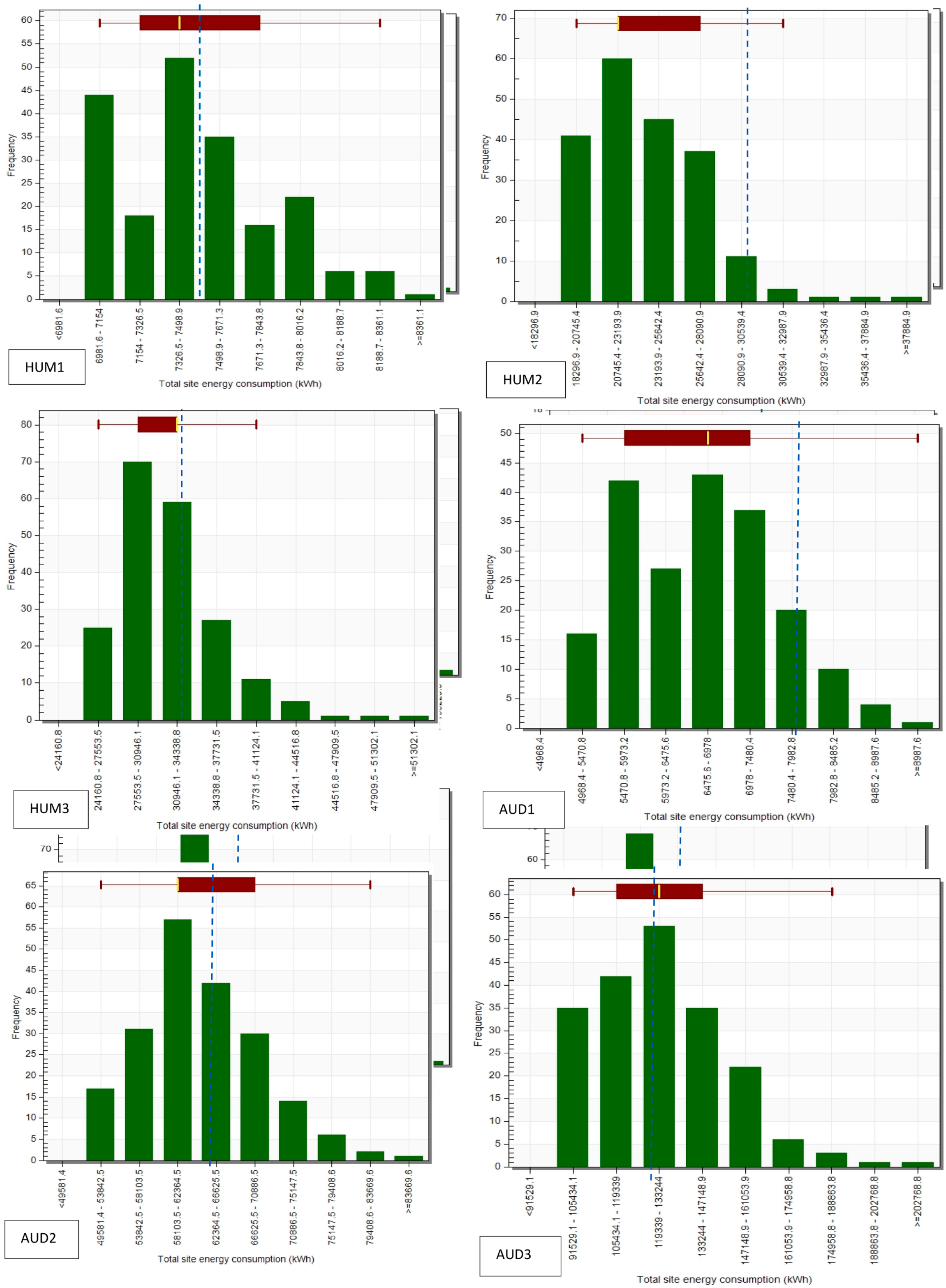


Fig. 7. Uncertainty analysis of the energy consumption (kWh) for the archetype models for the housing stock of Jordan.

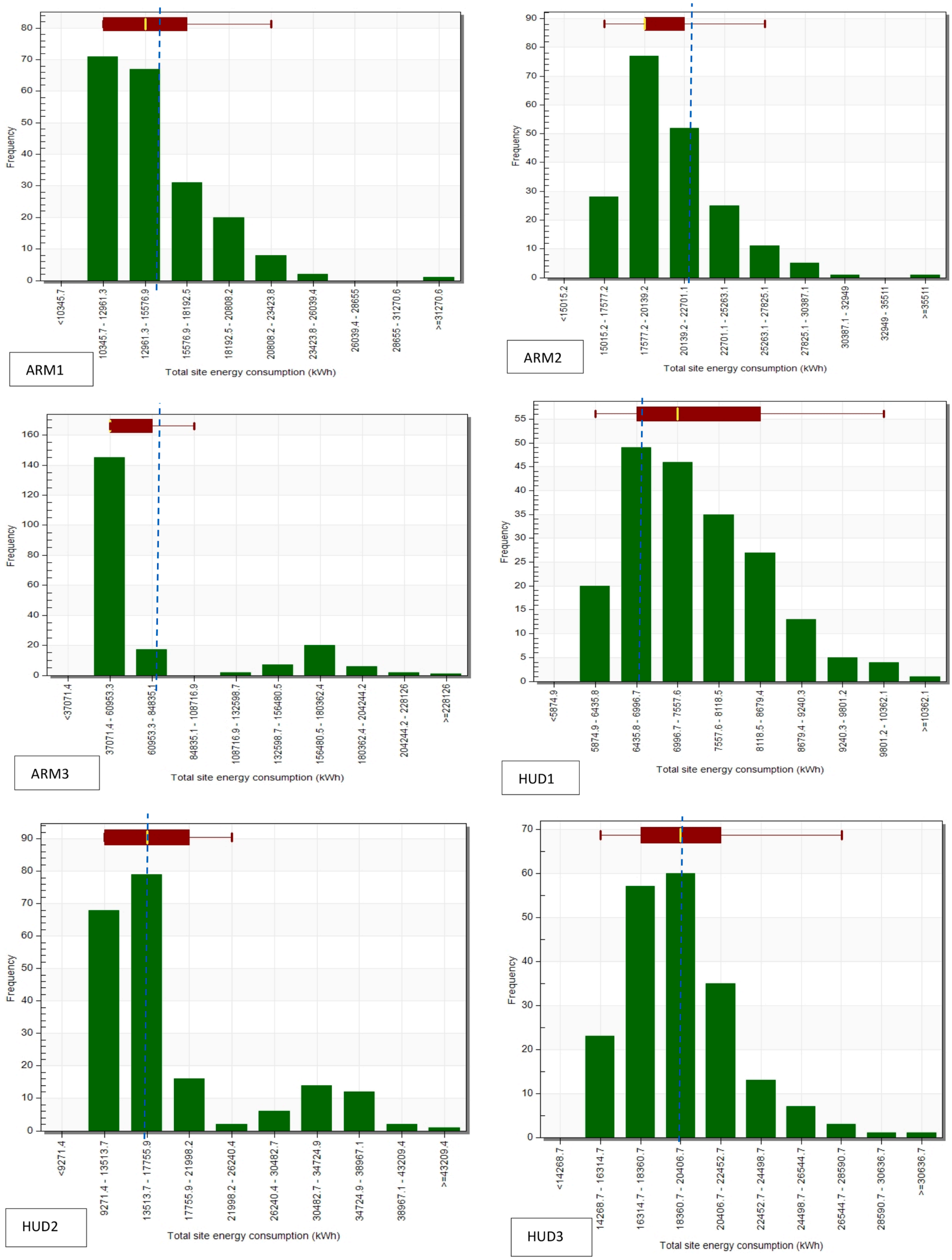


Fig. 7. (*continued*).

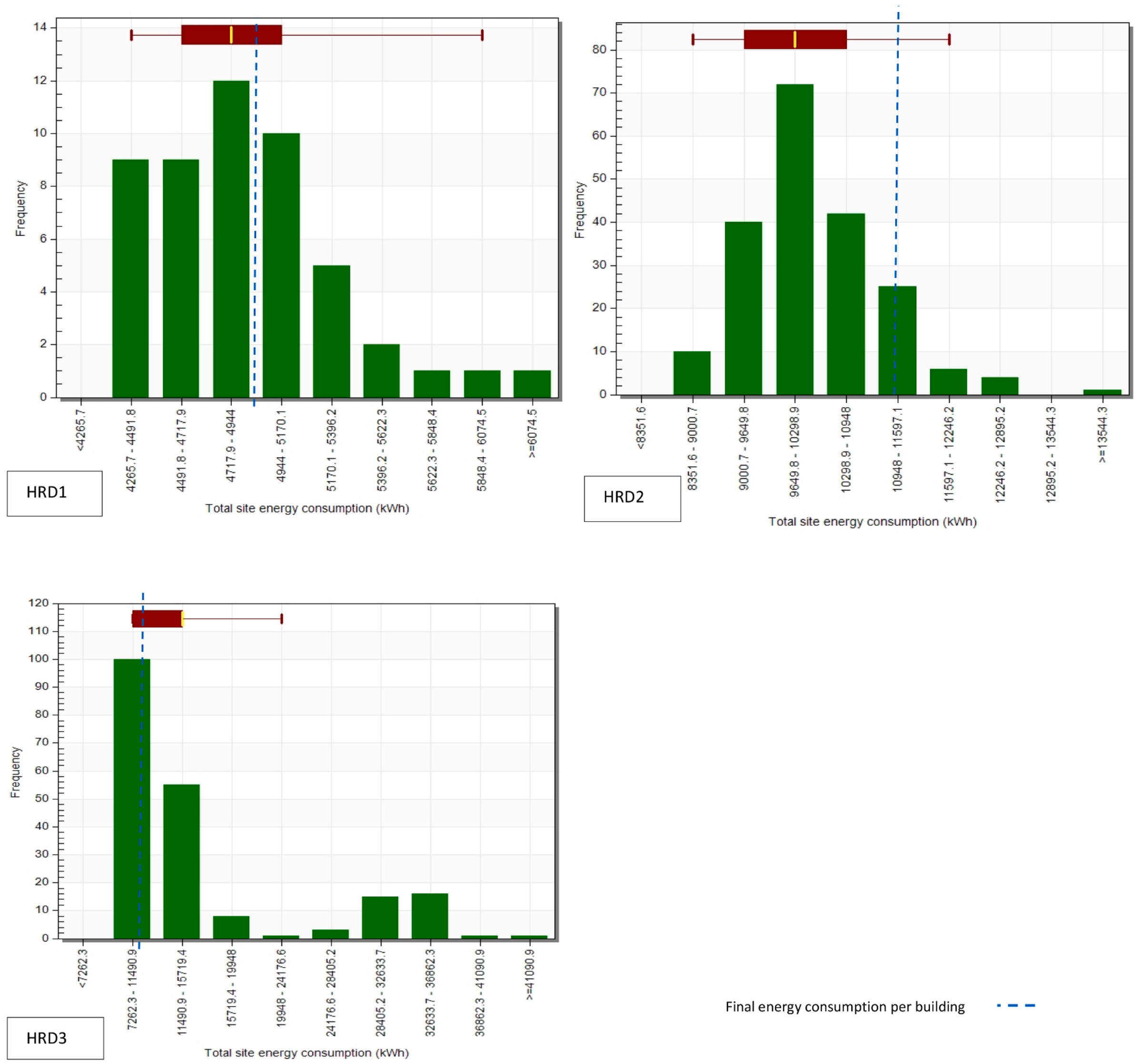


Fig. 7. (*continued*).

Table 11
Statistics on the distribution of the modelled domestic energy use in Jordan using 200 runs for each archetype model.

	AUM 1	AUM 2	AUM 3	HUM 1	HUM 2	HUM 3	HRM1
Baseline/ Energy model (kWh)	8,710	98,369	112,470	7,893	29,356	33,274	7,592
Uncertainty analysis/ mean (kWh)	9,144	101,777	104,452	7,793	24,567	32,709	7,479
	HRM 2	**HRM 3**	**AUD 1**	**AUD 2**	**AUD 3**	**ARM 1**	**ARM 2**
Baseline/ Energy model (kWh)	7,997	12,376	7,946	63,818	124,950	15,563	22,115
Uncertainty analysis/ mean (kWh)	7,717	12,276	6,663	62,785	126,247	14,717	20,643
	ARM 3	**HUD 1**	**HUD 2**	**HUD 3**	**HRD 1**	**HRD 2**	**HRD 3**
Baseline/ Energy model (kWh)	48,925	6,935	15,270	19,004	4,453	11,127	10,886
Uncertainty analysis/ mean (kWh)	72,813	7,507	18,072	19,559	4,891	10,199	15,276

that use GLS lighting systems is recommended.

Renewable microgeneration at building level and renewable and nuclear power generation upstream for the national electricity grid have the potential to be implemented to facilitate the decarbonisation of the electricity grid and building stock. These improvements will improve the resilience of the building stock against future climate.

It is essential to promote awareness regarding the potential for improving the performance of building envelopes. Furthermore, the implementation of obligatory building regulations for future constructions and the introduction of mandatory provisions for retrofitting projects are crucial to be undertaken. These measures will facilitate the integration of energy-efficient methodologies within both existing dwellings and new-builds.

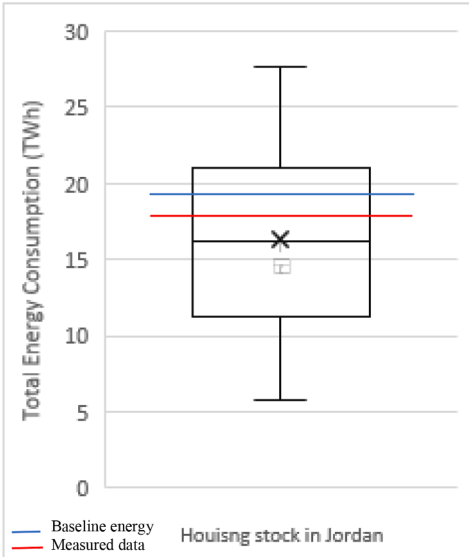


Fig. 8. Quantifying Energy Consumption Uncertainty in Jordan's Housing Stock: A Comparative Analysis with Measured Data.

5.4. Recommendations for future research

- Housing Stock model implications

Other future research will improve the building fabric and energy systems refurbishment strategies of housing stock in Jordan and investigate these improvements of the stock model using future weather files.

JHEM will provide a basis to implement Life Cycle Analysis (LCA) of carbon emissions of housing stock in Jordan considering the embodied carbon analysis of building components and operational carbon analysis during the use of building and its energy systems.

- Weather files

These future weather files could be used to predict the dwellings' energy performance in changing climate. The analysis could be expanded in future research to consider the effect of climate change on the thermal comfort of the existing dwellings. Especially in archetypes without mechanical comfort cooling.

It is also recommended to consider the effect of climate change on the urban heat island (UHI) phenomena and its impact on the weather conditions and the energy demand of housing stock in Jordan.

- Local data sources

It is expected that a continuous process of data collection and analysis will be required to update, complement, and validate existing information. This is likely to include the commissioning and undertaking of further field surveys.

5.5. Study limitations

One of the limitations of this study is the lack of information about buildings that are not fully utilized throughout the year, which leads to modelling assumptions that could affect the energy performance analysis at the national level. The surrounding composition, that provides shading on the building facades resulting a lower energy use, has not been considered when generating housing archetypes models as a result of the lack of data and the current absence of LiDAR (Light Detection and Ranging) technology and dataset in Jordan.

The available search results do not contain specific information about the current climate weather files offered by JGBC. Future research could explore the methodologies and datasets employed by JGBC in generating climate weather files, aiming to enhance the accuracy and effectiveness of energy analyses for buildings in Jordan.

6. Conclusion

A building stock model, JHEM, has been developed based on a building physics bottom-up approach using energy models for 21 archetypes representative of existing Jordan housing stock. The archetypes cover the characteristics of Jordan housing including typology, climate region, age-band, and urban–rural distribution. The stock model utilizes a dynamic building simulation tool, DesignBuilder, to determine energy consumption for all the archetypes. The annual consumption of the developed building stock model has been compared against the available total energy consumption data reported for Jordan dwellings. AUM and HUM archetypes within age-band from the 1950 s to after the 2000 s represent 83 % of the total energy consumed by the residential sector. The analysis has confirmed that heating is responsible for a significant energy demand in the housing stock in Jordan representing around 50 % of the total energy consumed by each archetype.

The housing stock models are to be used to determine the benefits of a wide range of energy retrofit measures to improve the performance of dwellings in Jordan. The generated housing stock model will feature prominently in the studies articulating life cycle assessments of Jordanian dwellings within different climate regions, facilitating the transition towards zero-carbon emissions buildings. Targeted refurbishment measures should be developed to maximize their economic, environmental, and social benefits.

CRediT authorship contribution statement

Reham Alasmar: Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yair Schwartz:** Writing – review & editing, Supervision. **Esfandiar Burman:** .

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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